PARK UNIT SHELVES

#BISC EVER BIOY

South Florida Ecosystem Restoration:

Scientific Information Needs

Science Subgroup

NATIONAL PARK SERVICE
WATER RESOURCES DIVISION
FORT COLLINS, COLORADO
RESOURCE ROOM PROPERTY

Digitized by the Internet Archive
in 2012 with funding from
LYRASIS Members and Sloan Foundation

http://archive.org/details/southfloridaecos00scie

SOUTH FLORIDA ECOSYSTEM RESTORATION:

SCIENTIFIC INFORMATION NEEDS

A Science Subgroup Report

to the

Working Group

of the

South Florida

Ecosystem Restoration Task Force

NATIONAL PARK SERVICE
WATER RESOURCES DIVISION
FORT COLLINS, COLORADO
RESOURCE ROOM PROPERTY

1996

SCIENCE SUBGROUP

Tom Armentano, NPS/ENP
Joan Browder, NOAA/NMFS
Bradford Brown, NOAA/NMFS, Co-chair
Gary Buckingham, USDA/ARS
Lawrence Burns*, EPA
Michael Crosby, NOAA/NOS
Kenneth Cummins, SFWMD
Truman Duncan, Miccosukee Tribe
Barry Glaz, USDA/ARS
Robert Halley, USGS
James Harriman, BIA
Lorraine Heisler, FGFWFC
Greg Hendricks, USDA/NRCS
Aaron Higer, USGS
Ronald Hilton, COE
Wiley Kitchens, USGS/BRD
Leo Minasian, FDEP
Douglas Morrison*, FWS
John Ogden, SFWMD
Peter Ortner, NOAA/OAR
Robert Pace, FWS
Mary Ann Poole, FGFWFC, Co-chair
Dan Scheidt, EPA
Hanley Smith, COE
Craig Tepper, Seminole Tribe
Michael Troyer, EPA
James Weaver, USGS/BRD, Co-chair

*Former SSG member integral to preparation of this report.

OTHER FEDERAL CONTRIBUTORS

Robert Ambrose, EPA
Rochelle Araujo, EPA
M. Craig Barber, EPA
Russell Bullock, EPA
Robert Fennema, NPS/ENP
Carole Goodyear, NOAA/NMFS
John Klein, NOAA/NOS
John Kucklick, NOAA/NMFS
Elmar Kurzbach, COE
William Loftus, USGS/BRD
Nicholas Loux, EPA
Mark Powell, NOAA/OAR
Patricia Richards, FWS
Michael Robblee, USGS/BRD
William Robertson, USGS/BRD
James Snyder, USGS/BRD
Michael Soukup, NPS
Nancy Thompson, NOAA/NMFS

EDITOR

Carole Goodyear, NOAA/NMFS

This report should be cited as:

Science Subgroup. 1996. South Florida Ecosystem Restoration: Scientific Information Needs. Report to the Working Group of the South Florida Ecosystem Restoration Task Force.

EXECUTIVE SUMMARY

This report on information needs is the first step in development of an ecosystem-based South Florida Comprehensive Science Plan required for the ecosystem approach mandated by the Interagency Task Force in its September 23, 1993, Agreement on South Florida Ecosystem Restoration. The modeling, monitoring, and special studies recommended in this document will provide the information basis for ecosystem management.

South Florida is a heterogeneous system of wetlands, uplands, and coastal and marine areas comprising at least 11 major physiographic provinces. It is dominated by the watersheds of the Kissimmee River, Lake Okeechobee, and the Everglades. Prior to drainage, wetlands covered most of central and southern Florida. Productivity of the predrainage wetlands was dependent on dynamic hydrologic storage and sheetflow, large spatial scale, and heterogeneity in habitat. The biological abundance and diversity the habitats once supported were maintained by the complex annual and long-term hydrologic patterns of the natural system, over which were superimposed sporadic events such as storms, fires, and freezes.

Human alterations in the hydrologic system beginning in the late 1800s have created water quality and water quantity problems for South Florida's natural systems, including the Everglades and the estuaries. Hydroperiods and hydropatterns, which relate to the duration, timing, and extent that wetlands are wet, have been greatly distorted. The quantity, timing, location, and quality of freshwater flow to estuaries have been greatly modified. The pace of deterioration seems to be increasing. Known wildlife populations are now a fraction of their size of even 30 years ago. Florida Bay is experiencing obvious catastrophic change manifested in massive seagrass dieoffs and noxious algal blooms. Even the reef tract is not immune to probable land-based detrimental influences.

South Florida's human population currently exceeds 5 million and is expanding rapidly. This expanding human presence has dramatically changed the South Florida Ecosystem. In addition to hydrologic alterations for flood control, the changes include an increasing water demand by agricultural and urban uses, while, at the same time, the water supply has actually been decreased by the conversion of land to agricultural and urban uses and by the shunting to the coast of fresh water that previously was stored in the wetlands, the soils, and the aquifers. Other changes are water quality and treatment problems, soil subsidence in the Everglades Agricultural Area, nutrient enrichment, pollution by contaminants, introduction of invasive non-native plants and animals, fragmentation of habitats and landscapes, loss of wetland areas and functions, altered fire regimes, and declines in reef and estuarine resources.

The problems of nonindigenous species, mercury contamination, pollution by pesticides and other contaminants, and preservation of endangered species are so serious and pervasive throughout South Florida that individual chapters are devoted to these cross-cutting problems on a region-wide basis, in addition to discussions in most of the subregion chapters. Holistic solutions to these problems will provide for more sustainable economic opportunities while at the same time improve the sustainability of the natural portions of the South Florida Ecosystem.

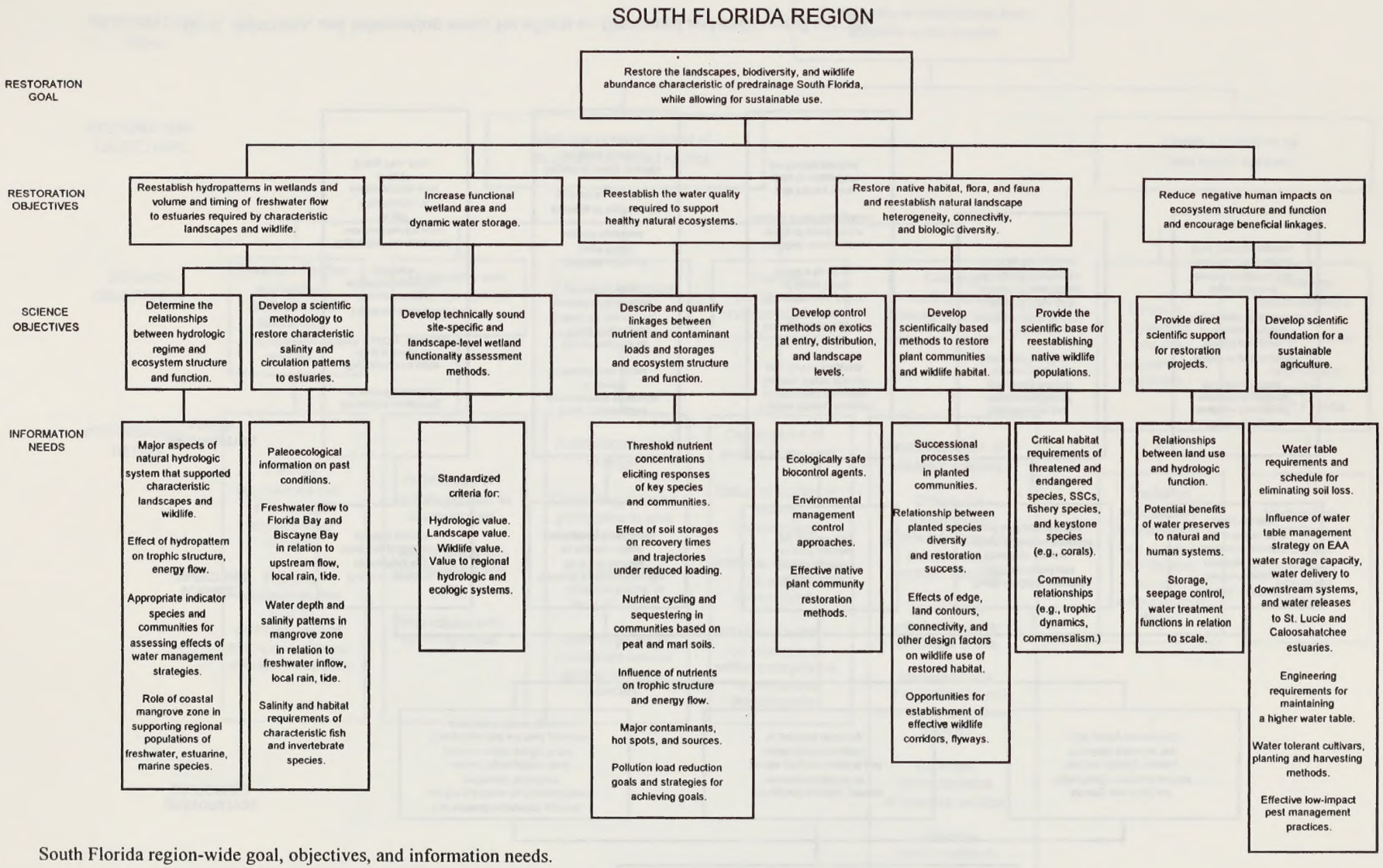
The overall goal of the restoration effort is to restore a sustainable ecosystem that preserves the valued properties of South Florida's natural systems and supports productive agriculture-, fishery-, and tourist-based economies and a high quality of urban life. The basic premise is that better water management will provide sustainability across both human and natural systems. Therefore, the working hypothesis is that hydrologic restoration is the prerequisite to ecosystem restoration. The highest priority science is that which determines how to modify the structure and operation of the hydrologic system to accomplish restoration.

The overall objective of the Science Subgroup is to develop an interagency, interdisciplinary science program that will guide restoration actions by determining relationships between ecosystem function and hydrologic regime and describing hydrologic conditions required to support the characteristic landscapes, biodiversity, and wildlife abundance of predrainage South Florida. The information needs presented in this document are directed at

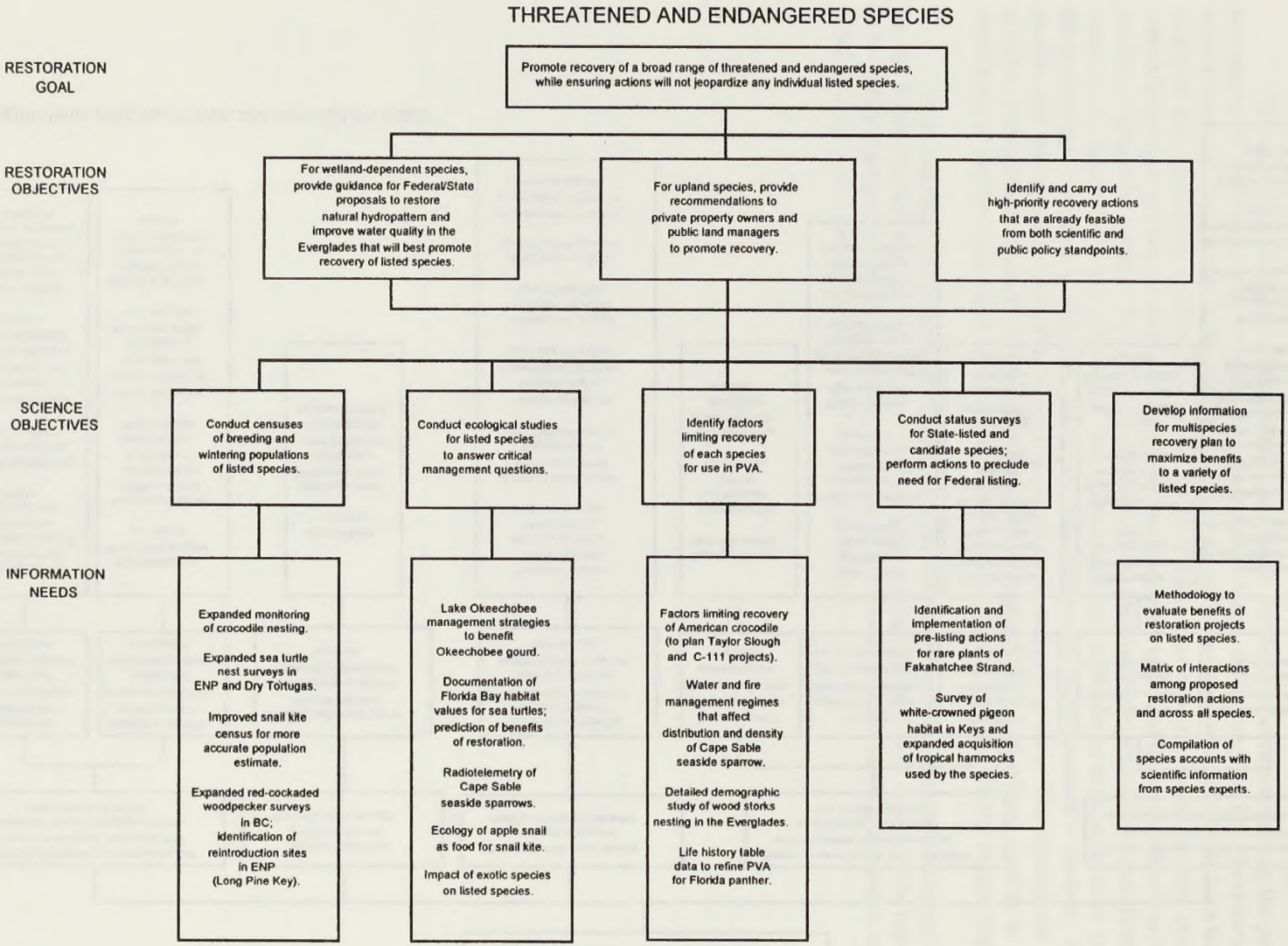
obtaining the data required to provide a scientific basis for management decisions and the information that could lead to increased beneficial interactions between natural and human communities.

The scientific investigations identified in this report are directed at characterizing the predrainage system, particularly its hydrology, and comparing it to the present system; determining the key characteristics of the former natural hydrologic system that supported the rich diversity and abundance of wildlife that have been lost; designing structural and operational modifications of the C&SF Project that would recreate the key characteristics of the natural hydrologic system; assessing the hydrologic and ecological results of these modifications; and modifying the design to make improvements. Particularly appropriate is the adaptive management approach, in which the measured outcome of management actions is used to make corrections and adjustments in those actions in order to improve the probability of achieving objectives. Adaptive management has three elements -- models, restoration support studies, and monitoring -- that must be used as coordinated, supportive tools. The operational foundation of the adaptive management approach is periodic environmental assessment, which utilizes models to predict outcomes, monitoring to test the predictions, and field and laboratory studies to provide critical supporting information.

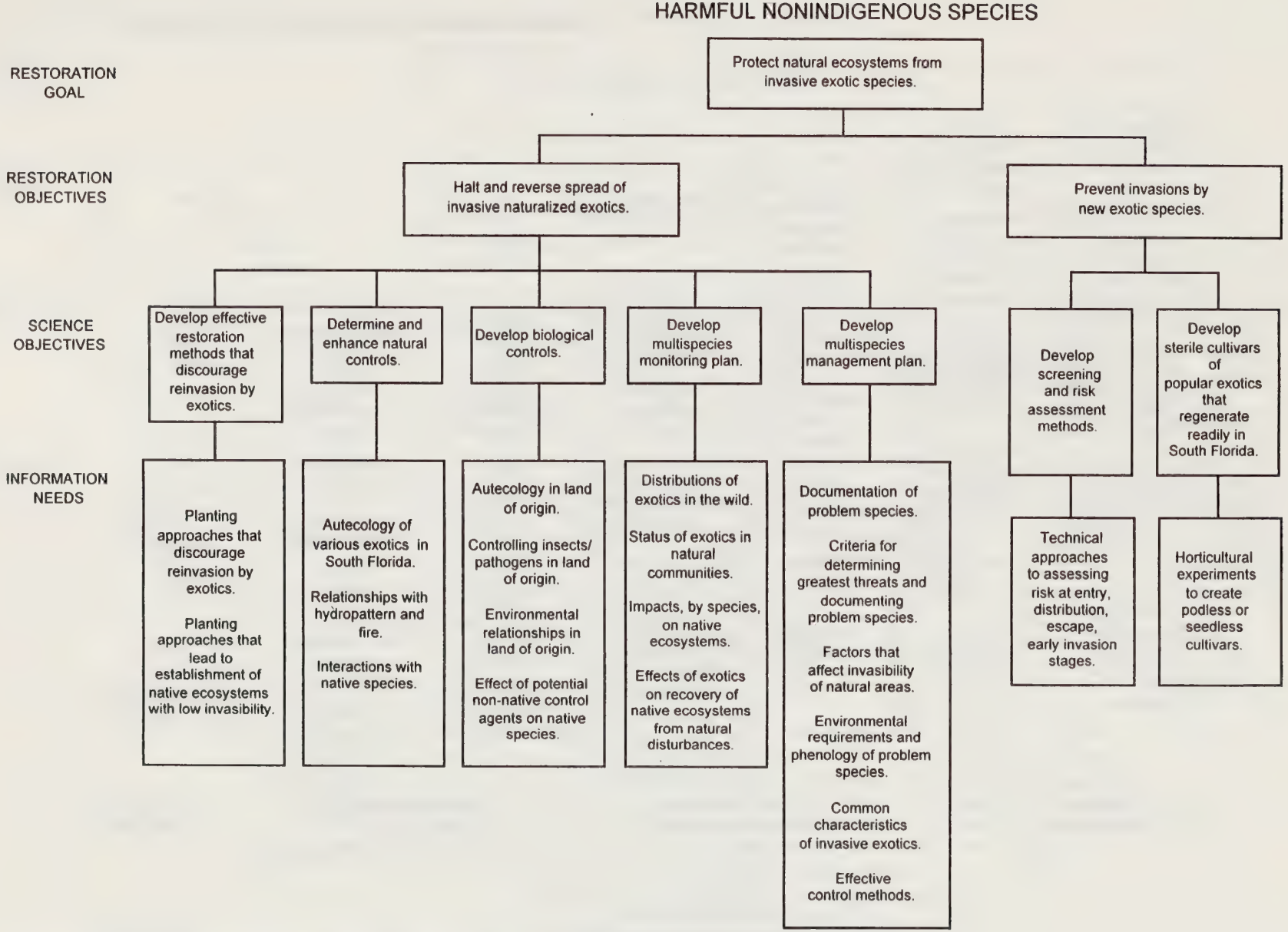
The scientific information needs in relation to the restoration goal and the restoration and science objectives for the South Florida Region, each of the 10 geographic subregions, and each region-wide topic are summarized in the following figures. The many information needs reflect the diversity of habitats and biotic communities within South Florida -- and also the diversity of ecological problems.


SOUTH FLORIDA REGION
RESTORATION GOAL
Restore the landscapes, biodiversity, and wildlife abundance characteristic of predrainage South Florida, while allowing for sustainable use.
RESTORATION OBJECTIVES
Reestablish hydropatterns in wetlands and volume and timing of freshwater flow to estuaries required by characteristic landscapes and wildlife.
Increase functional wetland area and dynamic water storage.
Reestablish the water quality required to support healthy natural ecosystems.
Restore native habitat, flora, and fauna and reestablish natural landscape heterogeneity, connectivity, and biologic diversity.
Reduce negative human impacts on ecosystem structure and function and encourage beneficial linkages.
SCIENCE OBJECTIVES
Determine the relationships between hydrologic regime and ecosystem structure and function.
Develop a scientific methodology to restore characteristic salinity and circulation patterns to estuaries.
Develop technically sound site-specific and landscape-level wetland functionality assessment methods.
Describe and quantify linkages between nutrient and contaminant loads and storages and ecosystem structure and function.
Develop control methods on exotics at entry, distribution, and landscape levels.
Develop scientifically based methods to restore plant communities and wildlife habitat.
Provide the scientific base for reestablishing native wildlife populations.
Provide direct scientific support for restoration projects.
Develop scientific foundation for a sustainable agriculture.
INFORMATION NEEDS
Major aspects of natural hydrologic system that supported characteristic landscapes and wildlife.
Effect of hydropattern on trophic structure, energy flow.
Appropriate indicator species and communities for assessing effects of water management strategies.
Role of coastal mangrove zone in supporting regional populations of freshwater, estuarine, marine species.
Paleoecological information on past conditions.
Freshwater flow to Florida Bay and Biscayne Bay in relation to upstream flow, local rain, tide.
Water depth and salinity patterns in mangrove zone in relation to freshwater inflow, local rain, tide.
Salinity and habitat requirements of characteristic fish and invertebrate species.
Standardized criteria for:
Hydrologic value.
Landscape value.
Wildlife value.
Value to regional hydrologic and ecologic systems.
Threshold nutrient concentrations eliciting responses of key species and communities.
Effect of soil storages on recovery times and trajectories under reduced loading.
Nutrient cycling and sequestering in communities based on peat and marl soils.
Influence of nutrients on trophic structure and energy flow.
Major contaminants, hot spots, and sources.
Pollution load reduction goals and strategies for achieving goals.
Ecologically safe biocontrol agents.
Environmental management control approaches.
Effective native plant community restoration methods.
Successional processes in planted communities.
Relationship between planted species diversity and restoration success.
Effects of edge, land contours, connectivity, and other design factors on wildlife use of restored habitat.
Opportunities for establishment of effective wildlife corridors, flyways.
Critical habitat requirements of threatened and endangered species, SSCs, fishery species, and keystone species (e.g., corals).
Community relationships (e.g., trophic dynamics, commensalism.)
Relationships between land use and hydrologic function.
Potential benefits of water preserves to natural and human systems.
Storage, seepage control, water treatment functions in relation to scale.
Water table requirements and schedule for eliminating soil loss.
Influence of water table management strategy on EAA water storage capacity, water delivery to downstream systems, and water releases to St. Lucie and Caloosahatchee estuaries.
Engineering requirements for maintaining a higher water table.
Water tolerant cultivars, planting and harvesting methods.
Effective low-impact pest management practices.

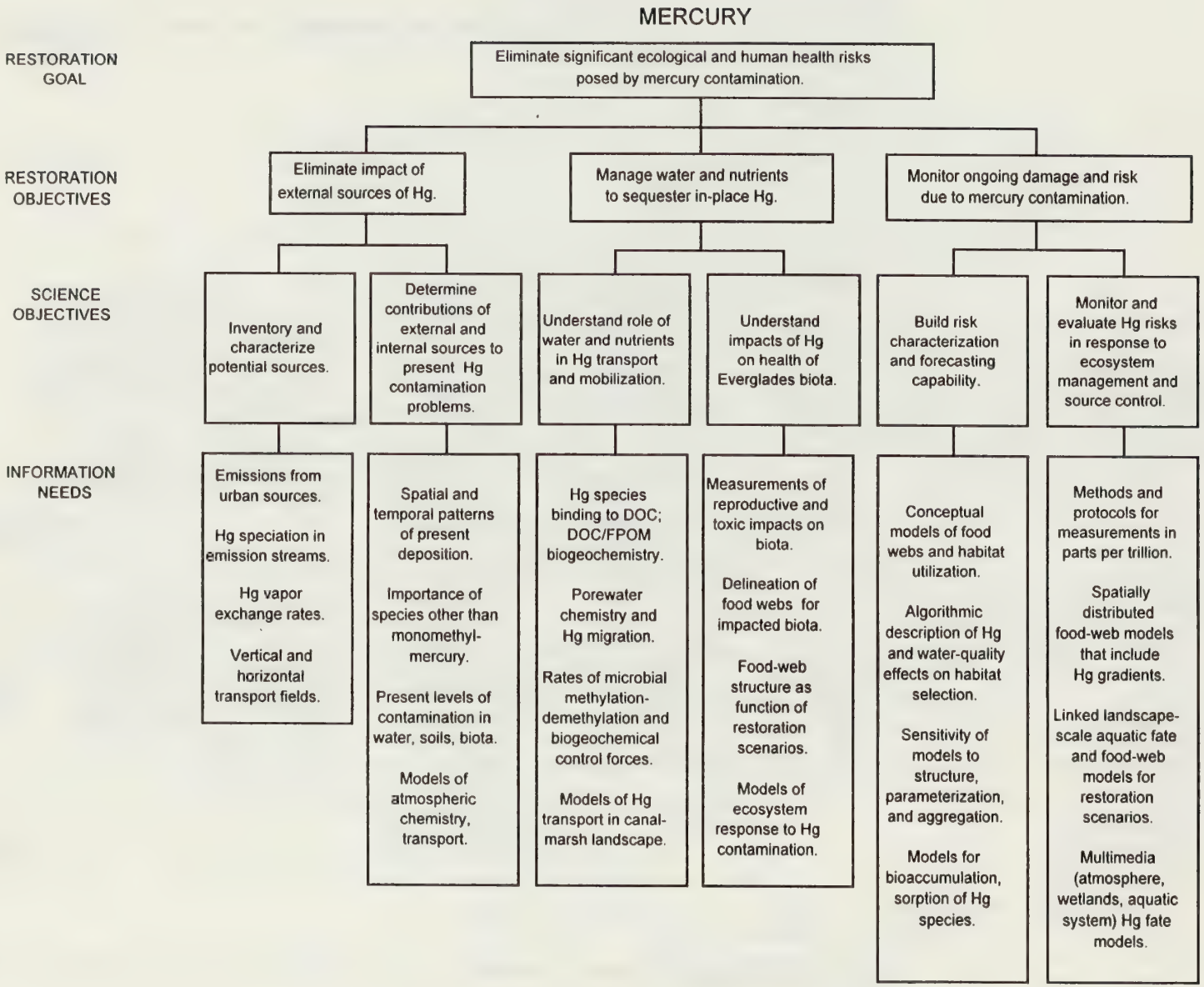
South Florida region-wide goal, objectives, and information needs.


THREATENED AND ENDANGERED SPECIES
RESTORATION GOAL
Promote recovery of a broad range of threatened and endangered species, while ensuring actions will not jeopardize any individual listed species.
RESTORATION OBJECTIVES
For wetland-dependent species, provide guidance for Federal/State proposals to restore natural hydropattern and improve water quality in the Everglades that will best promote recovery of listed species.
For upland species, provide recommendations to private property owners and public land managers to promote recovery.
Identify and carry out high-priority recovery actions that are already feasible from both scientific and public policy standpoints.
SCIENCE OBJECTIVES
Conduct censuses of breeding and wintering populations of listed species.
Conduct ecological studies for listed species to answer critical management questions.
Identify factors limiting recovery of each species for use in PVA.
Conduct status surveys for State-listed and candidate species; perform actions to preclude need for Federal listing.
Develop information for multispecies recovery plan to maximize benefits to a variety of listed species.
INFORMATION NEEDS
Expanded monitoring of crocodile nesting.
Expanded sea turtle nest surveys in ENP and Dry Tortugas.
Improved snail kite census for more accurate population estimate.
Expanded red-cockaded woodpecker surveys in BC; identification of reintroduction sites in ENP (Long Pine Key).
Lake Okeechobee management strategies to benefit Okeechobee gourd.
Documentation of Florida Bay habitat values for sea turtles; prediction of benefits of restoration.
Radiotelemetry of Cape Sable seaside sparrows.
Ecology of apple snail as food for snail kite.
Impact of exotic species on listed species.
Factors limiting recovery of American crocodile (to plan Taylor Slough and C-111 projects).
Water and fire management regimes that affect distribution and density of Cape Sable seaside sparrow.
Detailed demographic study of wood storks nesting in the Everglades.
Life history table data to refine PVA for Florida panther.
Identification and implementation of pre-listing actions for rare plants of Fakahatchee Strand.
Survey of white-crowned pigeon habitat in Keys and expanded acquisition of tropical hammocks used by the species.
Methodology to evaluate benefits of restoration projects on listed species.
Matrix of interactions among proposed restoration actions and across all species.
Compilation of species accounts with scientific information from species experts.

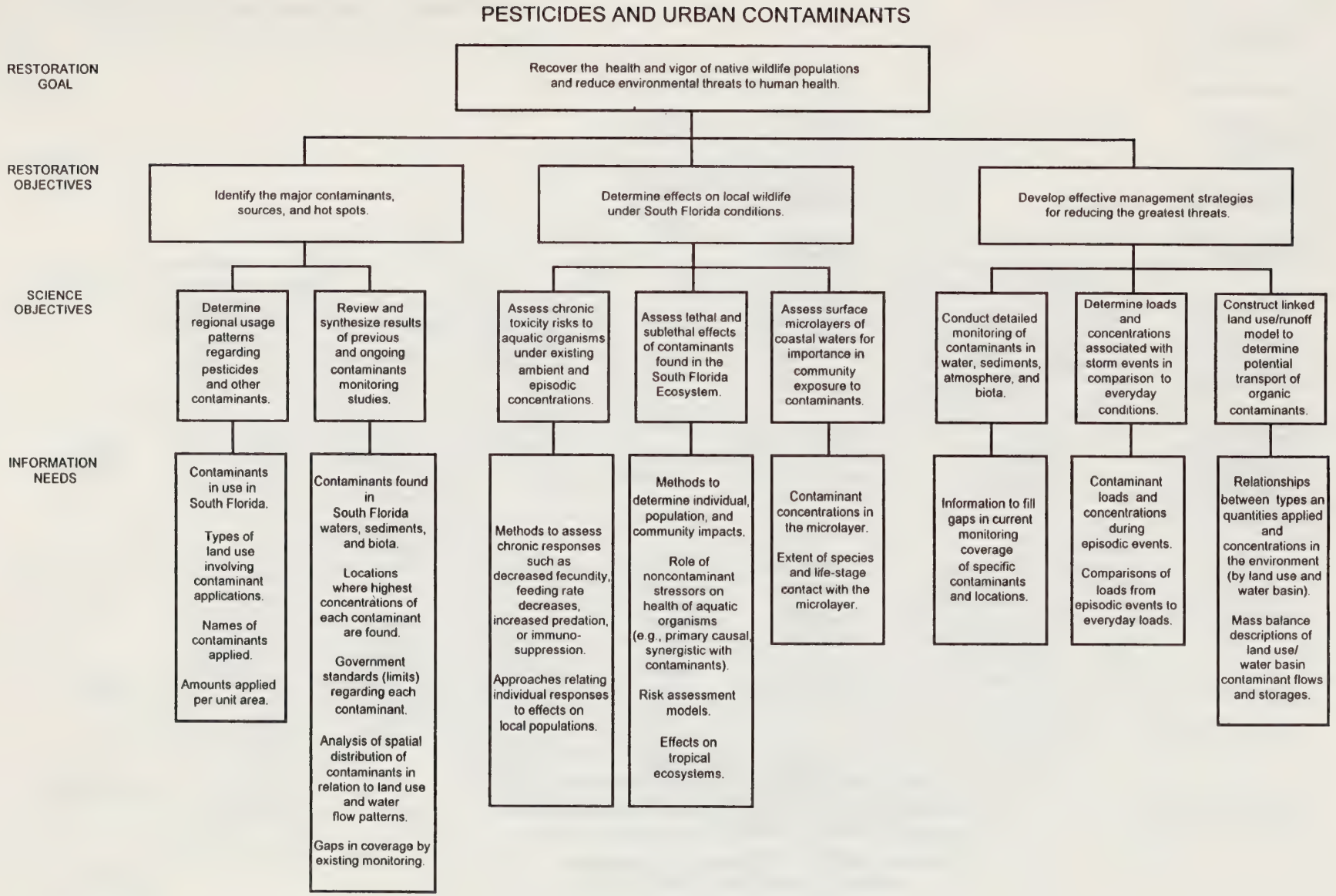
Goal, objectives, and information needs for efforts on threatened and endangered species.


HARMFUL NONINDIGENOUS SPECIES
RESTORATION GOAL
Protect natural ecosystems from invasive exotic species.
RESTORATION OBJECTIVES
Halt and reverse spread of invasive naturalized exotics.
Prevent invasions by new exotic species.
SCIENCE OBJECTIVES
Develop effective restoration methods that discourage reinvasion by exotics.
Determine and enhance natural controls.
Develop biological controls.
Develop multispecies monitoring plan.
Develop multispecies management plan.
Develop screening and risk assessment methods.
Develop sterile cultivars of popular exotics that regenerate readily in South Florida.
INFORMATION NEEDS
Planting approaches that discourage reinvasion by exotics.
Planting approaches that lead to establishment of native ecosystems with low invasibility.
Autecology of various exotics in South Florida.
Relationships with hydropattern and fire.
Interactions with native species.
Autecology in land of origin.
Controlling insects/ pathogens in land of origin.
Environmental relationships in land of origin.
Effect of potential non-native control agents on native species.
Distributions of exotics in the wild.
Status of exotics in natural communities.
Impacts, by species, on native ecosystems.
Effects of exotics on recovery of native ecosystems from natural disturbances.
Documentation of problem species.
Criteria for determining greatest threats and documenting problem species.
Factors that affect invasibility of natural areas.
Environmental requirements and phenology of problem species.
Common characteristics of invasive exotics.
Effective control methods.
Technical approaches to assessing risk at entry, distribution, escape, early invasion stages.
Horticultural experiments to create podless or seedless cultivars.

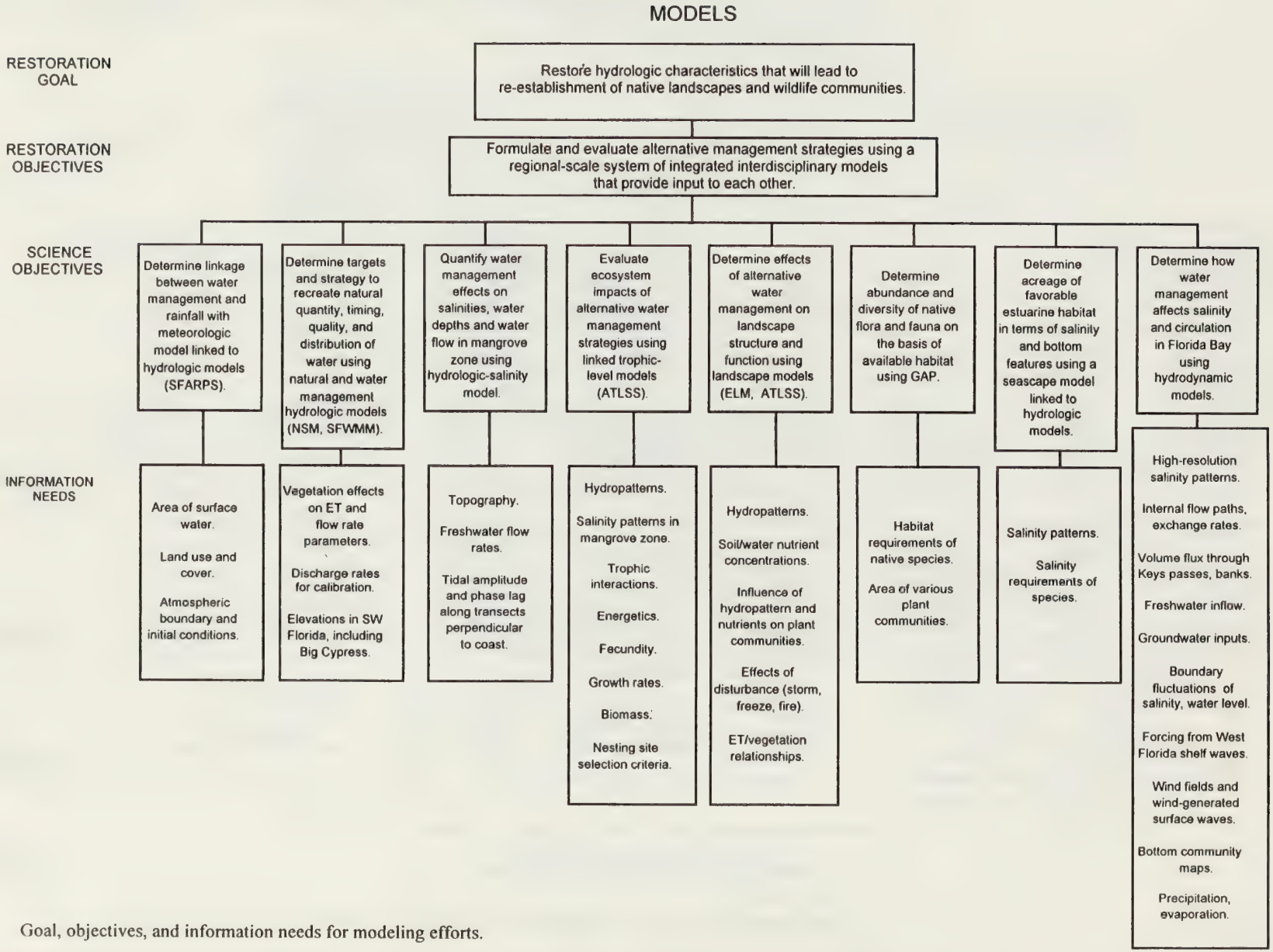
Goal, objectives, and information needs for efforts on nonindigenous species.


MERCURY
RESTORATION GOAL
Eliminate significant ecological and human health risks posed by mercury contamination.
RESTORATION OBJECTIVES
Eliminate impact of external sources of Hg.
Manage water and nutrients to sequester in-place Hg.
Monitor ongoing damage and risk due to mercury contamination.
SCIENCE OBJECTIVES
Inventory and characterize potential sources.
Determine contributions of external and internal sources to present Hg contamination problems.
Understand role of water and nutrients in Hg transport and mobilization.
Understand impacts of Hg on health of Everglades biota.
Build risk characterization and forecasting capability.
Monitor and evaluate Hg risks in response to ecosystem management and source control.
INFORMATION NEEDS
Emissions from urban sources.
Hg speciation in emission streams.
Hg vapor exchange rates.
Vertical and horizontal transport fields.
Spatial and temporal patterns of present deposition.
Importance of species other than monomethyl-mercury.
Present levels of contamination in water, soils, biota.
Models of atmospheric chemistry, transport.
Hg species binding to DOC; DOC/FPOM biogeochemistry.
Porewater chemistry and Hg migration.
Rates of microbial methylation-demethylation and biogeochemical control forces.
Models of Hg transport in canal-marsh landscape.
Measurements of reproductive and toxic impacts on biota.
Delineation of food webs for impacted biota.
Food-web structure as function of restoration scenarios.
Models of ecosystem response to Hg contamination.
Conceptual models of food webs and habitat utilization.
Algorithmic description of Hg and water-quality effects on habitat selection.
Sensitivity of models to structure, parameterization, and aggregation.
Models for bioaccumulation, sorption of Hg species.
Methods and protocols for measurements in parts per trillion.
Spatially distributed food-web models that include Hg gradients.
Linked landscape-scale aquatic fate and food-web models for restoration scenarios.
Multimedia (atmosphere, wetlands, aquatic system) Hg fate models.

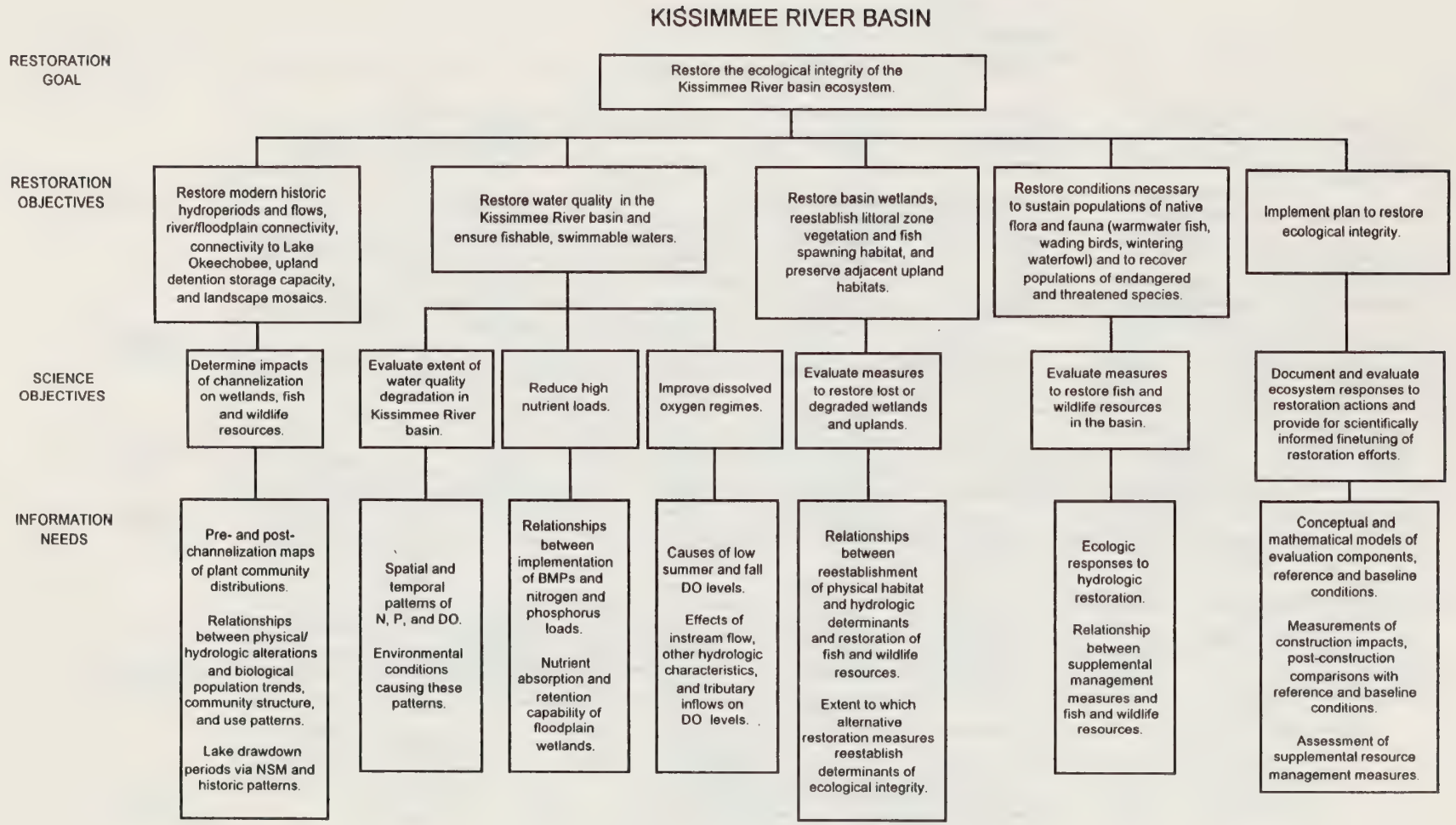
Goal, objectives, and information needs for efforts on mercury.


PESTICIDES AND URBAN CONTAMINANTS
RESTORATION GOAL
Recover the health and vigor of native wildlife populations and reduce environmental threats to human health.
RESTORATION OBJECTIVES
Identify the major contaminants, sources, and hot spots.
Determine effects on local wildlife under South Florida conditions.
Develop effective management strategies for reducing the greatest threats.
SCIENCE OBJECTIVES
Determine regional usage patterns regarding pesticides and other contaminants.
Review and synthesize results of previous and ongoing contaminants monitoring studies.
Assess chronic toxicity risks to aquatic organisms under existing ambient and episodic concentrations.
Assess lethal and sublethal effects of contaminants found in the South Florida Ecosystem.
Assess surface microlayers of coastal waters for importance in community exposure to contaminants.
Conduct detailed monitoring of contaminants in water, sediments, atmosphere, and biota.
Determine loads and concentrations associated with storm events in comparison to everyday conditions.
Construct linked land use/runoff model to determine potential transport of organic contaminants.
INFORMATION NEEDS
Contaminants in use in South Florida.
Types of land use involving contaminant applications.
Names of contaminants applied.
Amounts applied per unit area.
Contaminants found in South Florida waters, sediments, and biota.
Locations where highest concentrations of each contaminant are found.
Government standards (limits) regarding each contaminant.
Analysis of spatial distribution of contaminants in relation to land use and water flow patterns.
Gaps in coverage by existing monitoring.
Methods to assess chronic responses such as decreased fecundity, feeding rate decreases, increased predation, or immuno-suppression.
Approaches relating individual responses to effects on local populations.
Methods to determine individual, population, and community impacts.
Role of noncontaminant stressors on health of aquatic organisms (e.g., primary causal, synergistic with contaminants).
Risk assessment models.
Effects on tropical ecosystems.
Contaminant concentrations in the microlayer.
Extent of species and life-stage contact with the microlayer.
Information to fill gaps in current monitoring coverage of specific contaminants and locations.
Contaminant loads and concentrations during episodic events.
Comparisons of loads from episodic events to everyday loads.
Relationships between types an quantities applied and concentrations in the environment (by land use and water basin).
Mass balance descriptions of land use/ water basin contaminant flows and storages.

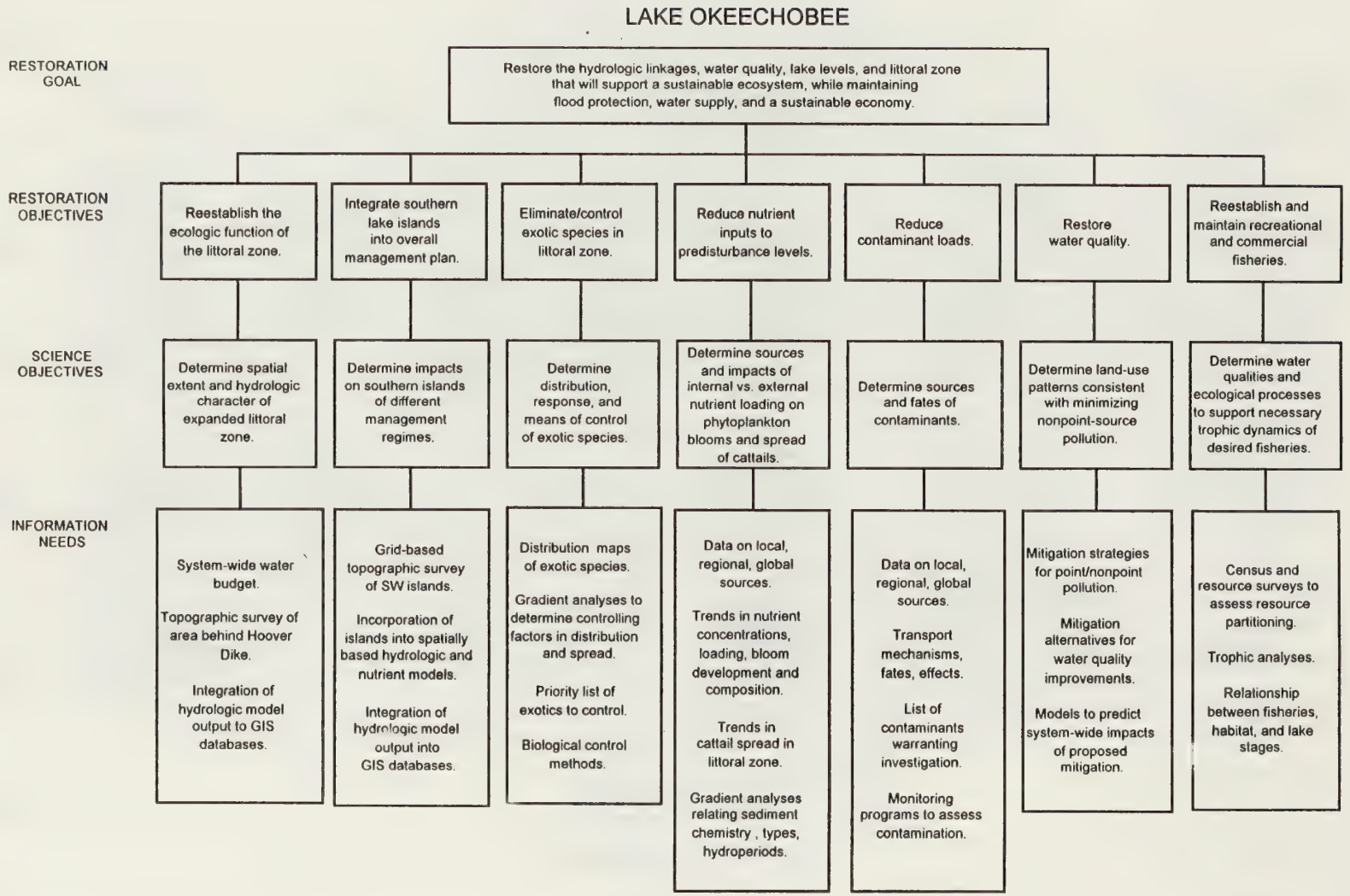
Goal, objectives, and information needs for efforts on pesticides and urban contaminants.


MODELS
RESTORATION GOAL
Restore hydrologic characteristics that will lead to re-establishment of native landscapes and wildlife communities.
RESTORATION OBJECTIVES
Formulate and evaluate alternative management strategies using a regional-scale system of integrated interdisciplinary models that provide input to each other.
SCIENCE OBJECTIVES
Determine linkage between water management and rainfall with meteorologic model linked to hydrologic models (SFARPS).
Determine targets and strategy to recreate natural quantity, timing, quality, and distribution of water using natural and water management hydrologic models (NSM, SFWMM).
Quantify water management effects on salinities, water depths and water flow in mangrove zone using hydrologic-salinity model.
Evaluate ecosystem impacts of alternative water management strategies using linked trophic-level models (ATLSS).
Determine effects of alternative water management on landscape structure and function using landscape models (ELM, ATLSS).
Determine abundance and diversity of native flora and fauna on the basis of available habitat using GAP.
Determine acreage of favorable estuarine habitat in terms of salinity and bottom features using a seascape model linked to hydrologic models.
Determine how water management affects salinity and circulation in Florida Bay using hydrodynamic models.
INFORMATION NEEDS
Area of surface water.
Land use and cover.
Atmospheric boundary and initial conditions.
Vegetation effects on ET and flow rate parameters.
Discharge rates for calibration.
Elevations in SW Florida, including Big Cypress.
Topography.
Freshwater flow rates.
Tidal amplitude and phase lag along transects perpendicular to coast.
Hydropatterns.
Salinity patterns in mangrove zone.
Trophic interactions.
Energetics.
Fecundity.
Growth rates.
Biomass.
Nesting site selection criteria.
Hydropatterns.
Soil/water nutrient concentrations.
Influence of hydropattern and nutrients on plant communities.
Effects of disturbance (storm, freeze, fire).
ET/vegetation relationships.
Habitat requirements of native species.
Area of various plant communities.
Salinity patterns.
Salinity requirements of species.
High-resolution salinity patterns.
Internal flow paths, exchange rates.
Volume flux through Keys passes, banks.
Freshwater inflow.
Groundwater inputs.
Boundary fluctuations of salinity, water level.
Forcing from West Florida shelf waves.
Wind fields and wind-generated surface waves.
Bottom community maps.
Precipitation, evaporation.

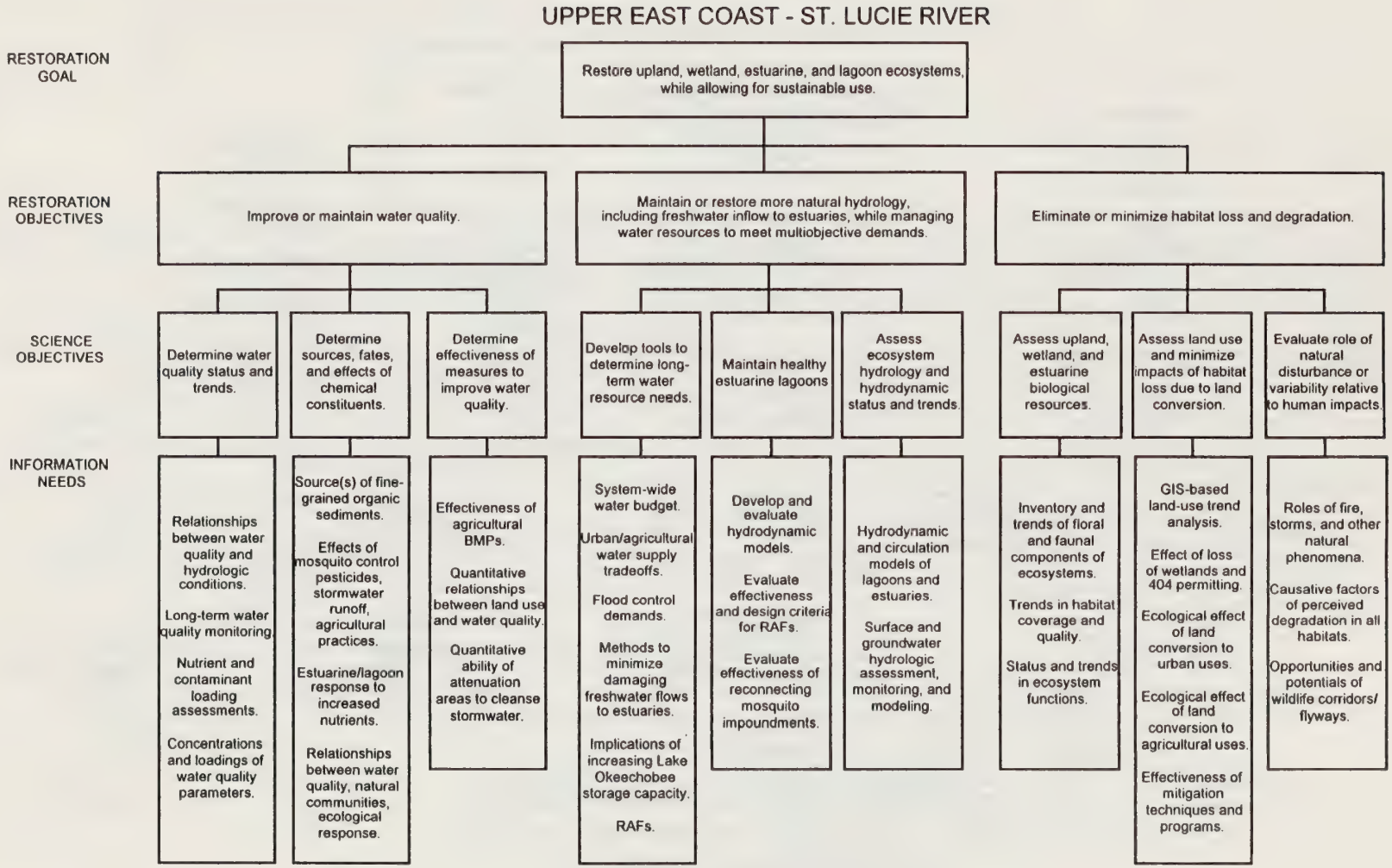
Goal, objectives, and information needs for modeling efforts.


KISSIMMEE RIVER BASIN
RESTORATION GOAL
Restore the ecological integrity of the Kissimmee River basin ecosystem.
RESTORATION OBJECTIVES
Restore modern historic hydroperiods and flows, river/floodplain connectivity, connectivity to Lake Okeechobee, upland detention storage capacity, and landscape mosaics.
Restore water quality in the Kissimmee River basin and ensure fishable, swimmable waters.
Restore basin wetlands, reestablish littoral zone vegetation and fish spawning habitat, and preserve adjacent upland habitats.
Restore conditions necessary to sustain populations of native flora and fauna (warmwater fish, wading birds, wintering waterfowl) and to recover populations of endangered and threatened species.
Implement plan to restore ecological integrity.
SCIENCE OBJECTIVES
Determine impacts of channelization on wetlands, fish and wildlife resources.
Evaluate extent of water quality degradation in Kissimmee River basin.
Reduce high nutrient loads.
Improve dissolved oxygen regimes.
Evaluate measures to restore lost or degraded wetlands and uplands.
Evaluate measures to restore fish and wildlife resources in the basin.
Document and evaluate ecosystem responses to restoration actions and provide for scientifically informed finetuning of restoration efforts.
INFORMATION NEEDS
Pre- and post-channelization maps of plant community distributions.
Relationships between physical/hydrologic alterations and biological population trends, community structure, and use patterns.
Lake drawdown periods via NSM and historic patterns.
Spatial and temporal patterns of N, P, and DO.
Environmental conditions causing these patterns.
Relationships between implementation of BMPs and nitrogen and phosphorus loads.
Nutrient absorption and retention capability of floodplain wetlands.
Causes of low summer and fall DO levels.
Effects of instream flow, other hydrologic characteristics, and tributary inflows on DO levels.
Relationships between reestablishment of physical habitat and hydrologic determinants and restoration of fish and wildlife resources.
Extent to which alternative restoration measures reestablish determinants of ecological integrity.
Ecologic responses to hydrologic restoration.
Relationship between supplemental management measures and fish and wildlife resources.
Conceptual and mathematical models of evaluation components, reference and baseline conditions.
Measurements of construction impacts, post-construction comparisons with reference and baseline conditions.
Assessment of supplemental resource management measures.

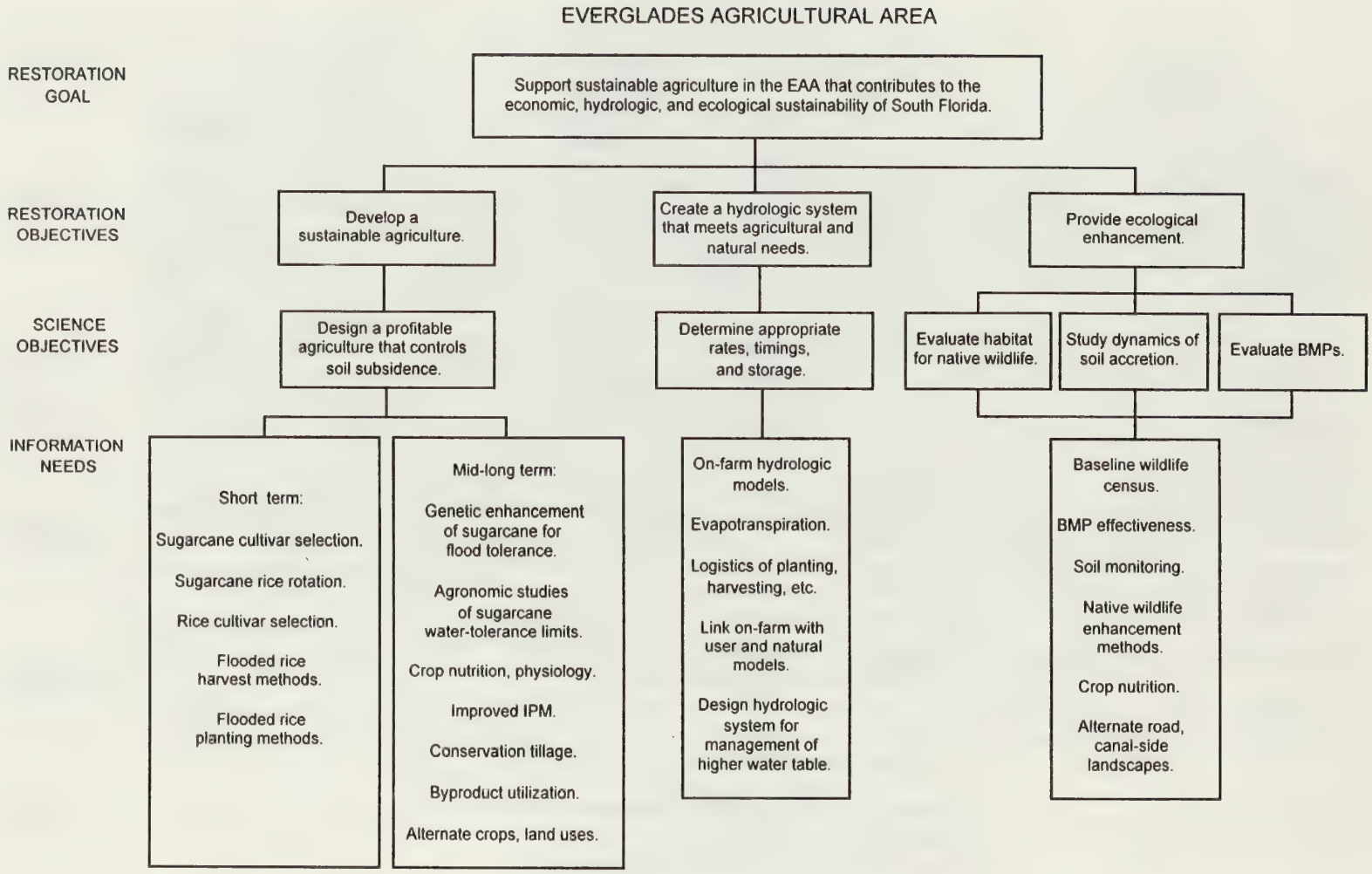
Goal, objectives, and information needs for Subregion 1.


LAKE OKEECHOBEE
RESTORATION GOAL
Restore the hydrologic linkages, water quality, lake levels, and littoral zone that will support a sustainable ecosystem, while maintaining flood protection, water supply, and a sustainable economy.
RESTORATION OBJECTIVES
Reestablish the ecologic function of the littoral zone.
Integrate southern lake islands into overall management plan.
Eliminate/control exotic species in littoral zone.
Reduce nutrient inputs to predisturbance levels.
Reduce contaminant loads.
Restore water quality.
Reestablish and maintain recreational and commercial fisheries.
SCIENCE OBJECTIVES
Determine spatial extent and hydrologic character of expanded littoral zone.
Determine impacts on southern islands of different management regimes.
Determine distribution, response, and means of control of exotic species.
Determine sources and impacts of internal vs. external nutrient loading on phytoplankton blooms and spread of cattails.
Determine sources and fates of contaminants.
Determine land-use patterns consistent with minimizing nonpoint-source pollution.
Determine water qualities and ecological processes to support necessary trophic dynamics of desired fisheries.
INFORMATION NEEDS
System-wide water budget.
Topographic survey of area behind Hoover Dike.
Integration of hydrologic model output to GIS databases.
Grid-based topographic survey of SW islands.
Incorporation of islands into spatially based hydrologic and nutrient models.
Integration of hydrologic model output into GIS databases.
Distribution maps of exotic species.
Gradient analyses to determine controlling factors in distribution and spread.
Priority list of exotics to control.
Biological control methods.
Data on local, regional, global sources.
Trends in nutrient concentrations, loading, bloom development and composition.
Trends in cattail spread in littoral zone.
Gradient analyses relating sediment chemistry , types, hydroperiods.
Data on local, regional, global sources.
Transport mechanisms, fates, effects.
List of contaminants warranting investigation.
Monitoring programs to assess contamination.
Mitigation strategies for point/nonpoint pollution.
Mitigation alternatives for water quality improvements.
Models to predict system-wide impacts of proposed mitigation.
Census and resource surveys to assess resource partitioning.
Trophic analyses.
Relationship between fisheries, habitat, and lake stages.

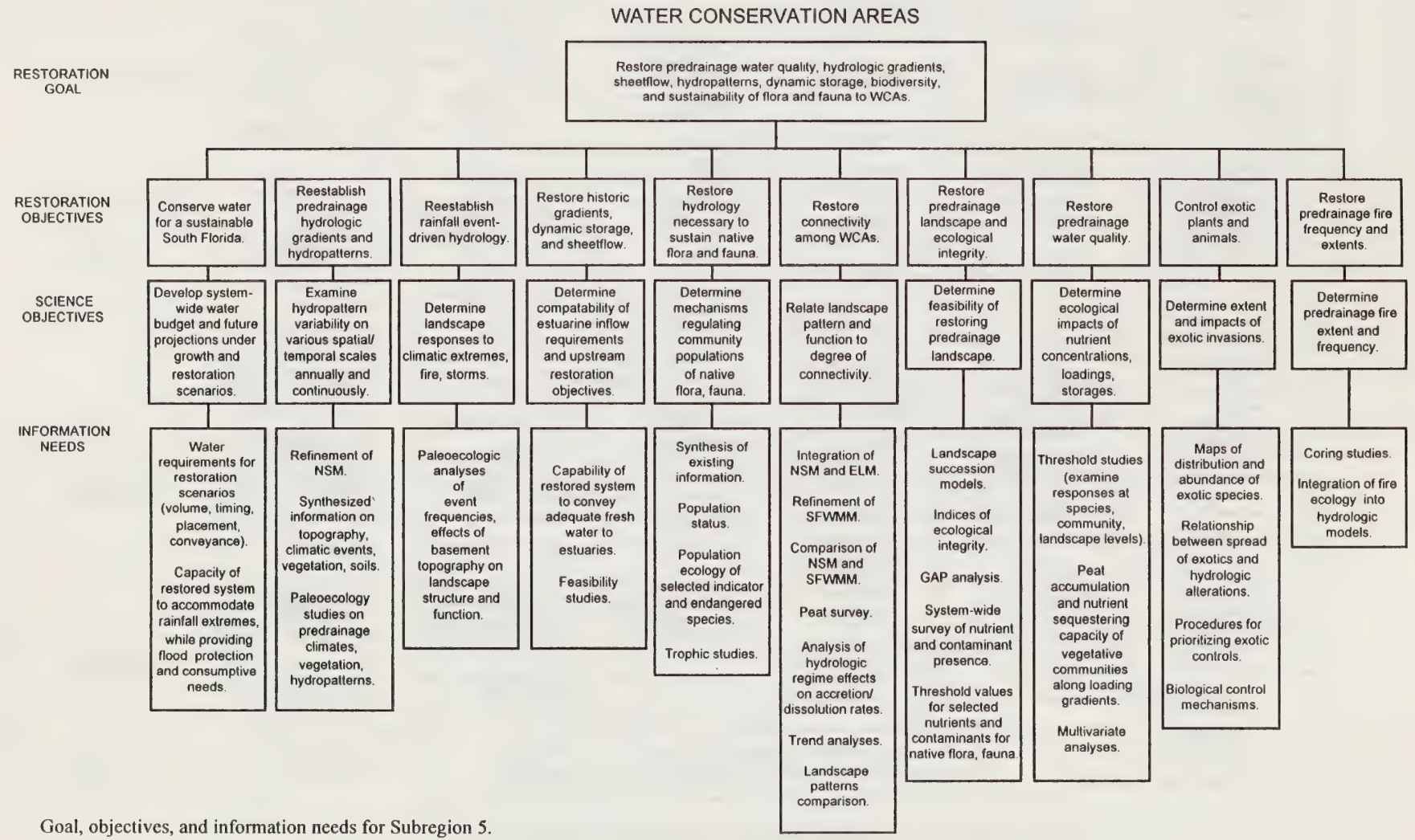
Goal, objectives, and information needs for Subregion 2.


UPPER EAST COAST - ST. LUCIE RIVER
RESTORATION GOAL
Restore upland, wetland, estuarine, and lagoon ecosystems, while allowing for sustainable use.
RESTORATION OBJECTIVES
Improve or maintain water quality.
Maintain or restore more natural hydrology, including freshwater inflow to estuaries, while managing water resources to meet multiobjective demands.
Eliminate or minimize habitat loss and degradation.
SCIENCE OBJECTIVES
Determine water quality status and trends.
Determine sources, fates, and effects of chemical constituents.
Determine effectiveness of measures to improve water quality.
Develop tools to determine long-term water resource needs.
Maintain healthy estuarine lagoons
Assess ecosystem hydrology and hydrodynamic status and trends.
Assess upland, wetland, and estuarine biological resources.
Assess land use and minimize impacts of habitat loss due to land conversion.
Evaluate role of natural disturbance or variability relative to human impacts.
INFORMATION NEEDS
Relationships between water quality and hydrologic conditions.
Long-term water quality monitoring.
Nutrient and contaminant loading assessments.
Concentrations and loadings of water quality parameters.
Source(s) of fine-grained organic sediments.
Effects of mosquito control pesticides, stormwater runoff, agricultural practices.
Estuarine/lagoon response to increased nutrients.
Relationships between water quality, natural communities, ecological response.
Effectiveness of agricultural BMPs.
Quantitative relationships between land use and water quality.
Quantitative ability of attenuation areas to cleanse stormwater.
System-wide water budget.
Urban/agricultural water supply tradeoffs.
Flood control demands.
Methods to minimize damaging freshwater flows to estuaries.
Implications of increasing Lake Okeechobee storage capacity.
RAFs.
Develop and evaluate hydrodynamic models.
Evaluate effectiveness and design criteria for RAFs.
Evaluate effectiveness of reconnecting mosquito impoundments.
Hydrodynamic and circulation models of lagoons and estuaries.
Surface and groundwater hydrologic assessment, monitoring, and modeling.
Inventory and trends of floral and faunal components of ecosystems.
Trends in habitat coverage and quality.
Status and trends in ecosystem functions.
GIS-based land-use trend analysis.
Effect of loss of wetlands and 404 permitting.
Ecological effect of land conversion to urban uses.
Ecological effect of land conversion to agricultural uses.
Effectiveness of mitigation techniques and programs.
Roles of fire, storms, and other natural phenomena.
Causative factors of perceived degradation in all habitats.
Opportunities and potentials of wildlife corridors/ flyways.

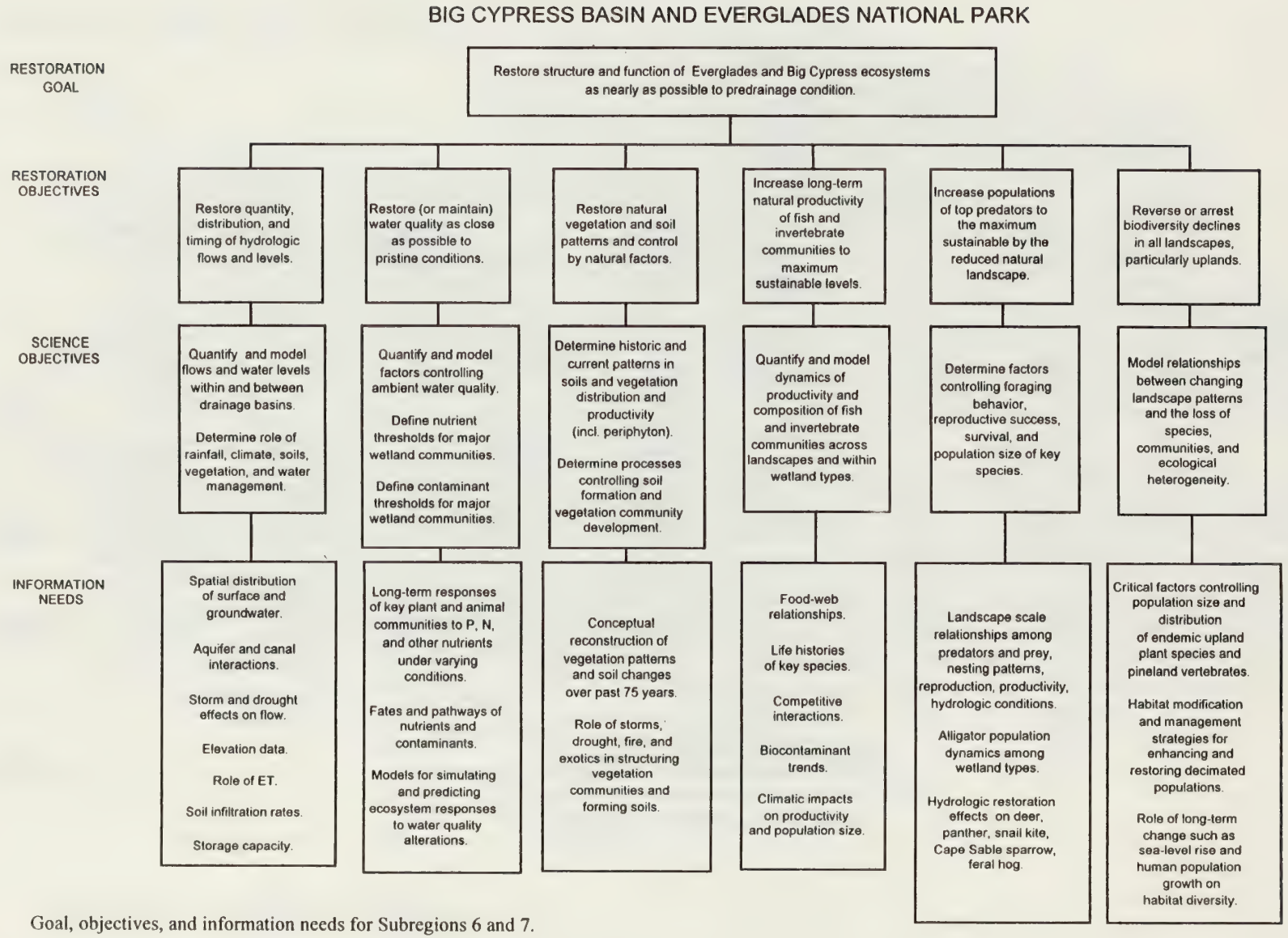
Goal, objectives, and information needs for Subregion 3.


EVERGLADES AGRICULTURAL AREA
RESTORATION GOAL
Support sustainable agriculture in the EAA that contributes to the economic, hydrologic, and ecological sustainability of South Florida.
RESTORATION OBJECTIVES
Develop a sustainable agriculture.
Create a hydrologic system that meets agricultural and natural needs.
Provide ecological enhancement.
SCIENCE OBJECTIVES
Design a profitable agriculture that controls soil subsidence.
Determine appropriate rates, timings, and storage.
Evaluate habitat for native wildlife.
Study dynamics of soil accretion.
Evaluate BMPs.
INFORMATION NEEDS
Short term:
Sugarcane cultivar selection.
Sugarcane rice rotation.
Rice cultivar selection.
Flooded rice harvest methods.
Flooded rice planting methods.
Mid-long term:
Genetic enhancement of sugarcane for flood tolerance.
Agronomic studies of sugarcane water-tolerance limits.
Crop nutrition, physiology.
Improved IPM.
Conservation tillage.
Byproduct utilization.
Alternate crops, land uses.
On-farm hydrologic models.
Evapotranspiration.
Logistics of planting, harvesting, etc.
Link on-farm with user and natural models.
Design hydrologic system for management of higher water table.
Baseline wildlife census.
BMP effectiveness.
Soil monitoring.
Native wildlife enhancement methods.
Crop nutrition.
Alternate road, canal-side landscapes.

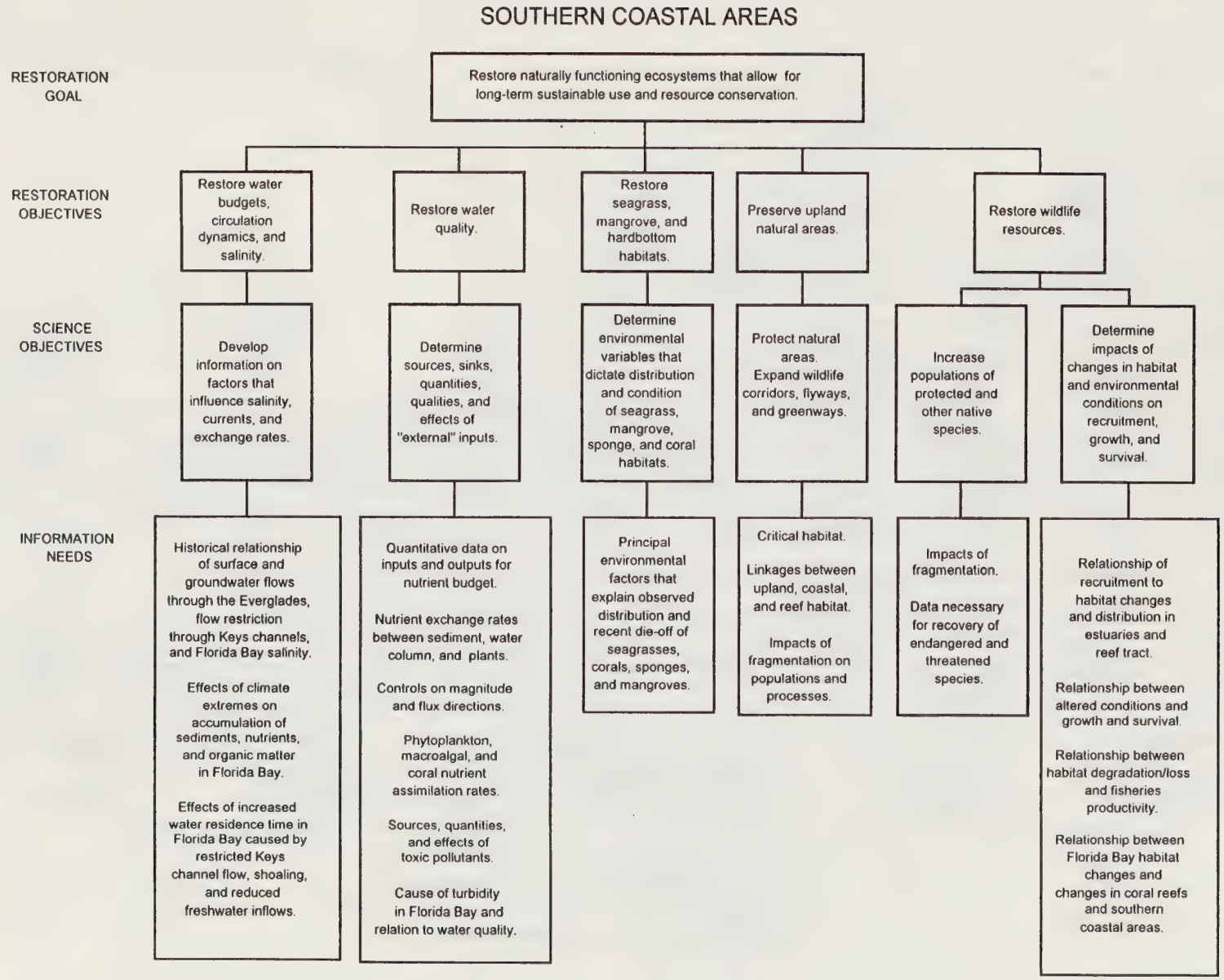
Goal, objectives, and information needs for Subregion 4.


WATER CONSERVATION AREAS
RESTORATION GOAL
Restore predrainage water quality, hydrologic gradients, sheetflow, hydropatterns, dynamic storage, biodiversity, and sustainability of flora and fauna to WCAs.
RESTORATION OBJECTIVES
Conserve water for a sustainable South Florida.
Reestablish predrainage hydrologic gradients and hydropatterns.
Reestablish rainfall event-driven hydrology.
Restore historic gradients, dynamic storage, and sheetflow.
Restore hydrology necessary to sustain native flora and fauna.
Restore connectivity among WCAs.
Restore predrainage landscape and ecological integrity.
Restore predrainage water quality.
Control exotic plants and animals.
Restore predrainage fire frequency and extents.
SCIENCE OBJECTIVES
Develop system-wide water budget and future projections under growth and restoration scenarios.
Examine hydropattern variability on various spatial/ temporal scales annually and continuously.
Determine landscape responses to climatic extremes, fire, storms.
Determine compatability of estuarine inflow requirements and upstream restoration objectives.
Determine mechanisms regulating community populations of native flora, fauna.
Relate landscape pattern and function to degree of connectivity.
Determine feasibility of restoring predrainage landscape.
Determine ecological impacts of nutrient concentrations, loadings, storages.
Determine extent and impacts of exotic invasions.
Determine predrainage fire extent and frequency.
INFORMATION NEEDS
Water requirements for restoration scenarios (volume, timing, placement, conveyance).
Capacity of restored system to accommodate rainfall extremes, while providing flood protection and consumptive needs.
Refinement of NSM.
Synthesized information on topography, climatic events, vegetation, soils.
Paleoecology studies on predrainage climates, vegetation, hydropatterns.
Paleoecologic analyses of event frequencies, effects of basement topography on landscape structure and function.
Capability of restored system to convey adequate fresh water to estuaries.
Feasibility studies.
Synthesis of existing information.
Population status.
Population ecology of selected indicator and endangered species.
Trophic studies.
Integration of NSM and ELM.
Refinement of SFWMM.
Comparison of NSM and SFWMM.
Peat survey.
Analysis of hydrologic regime effects on accretion/ dissolution rates.
Trend analyses.
Landscape patterns comparison.
Landscape succession models.
Indices of ecological integrity.
GAP analysis.
System-wide survey of nutrient and contaminant presence.
Threshold values for selected nutrients and contaminants for native flora, fauna.
Threshold studies (examine responses at species, community, landscape levels).
Peat accumulation and nutrient sequestering capacity of vegetative communities along loading gradients.
Multivariate analyses.
Maps of distribution and abundance of exotic species.
Relationship between spread of exotics and hydrologic alterations.
Procedures for prioritizing exotic controls.
Biological control mechanisms.
Coring studies.
Integration of fire ecology into hydrologic models.

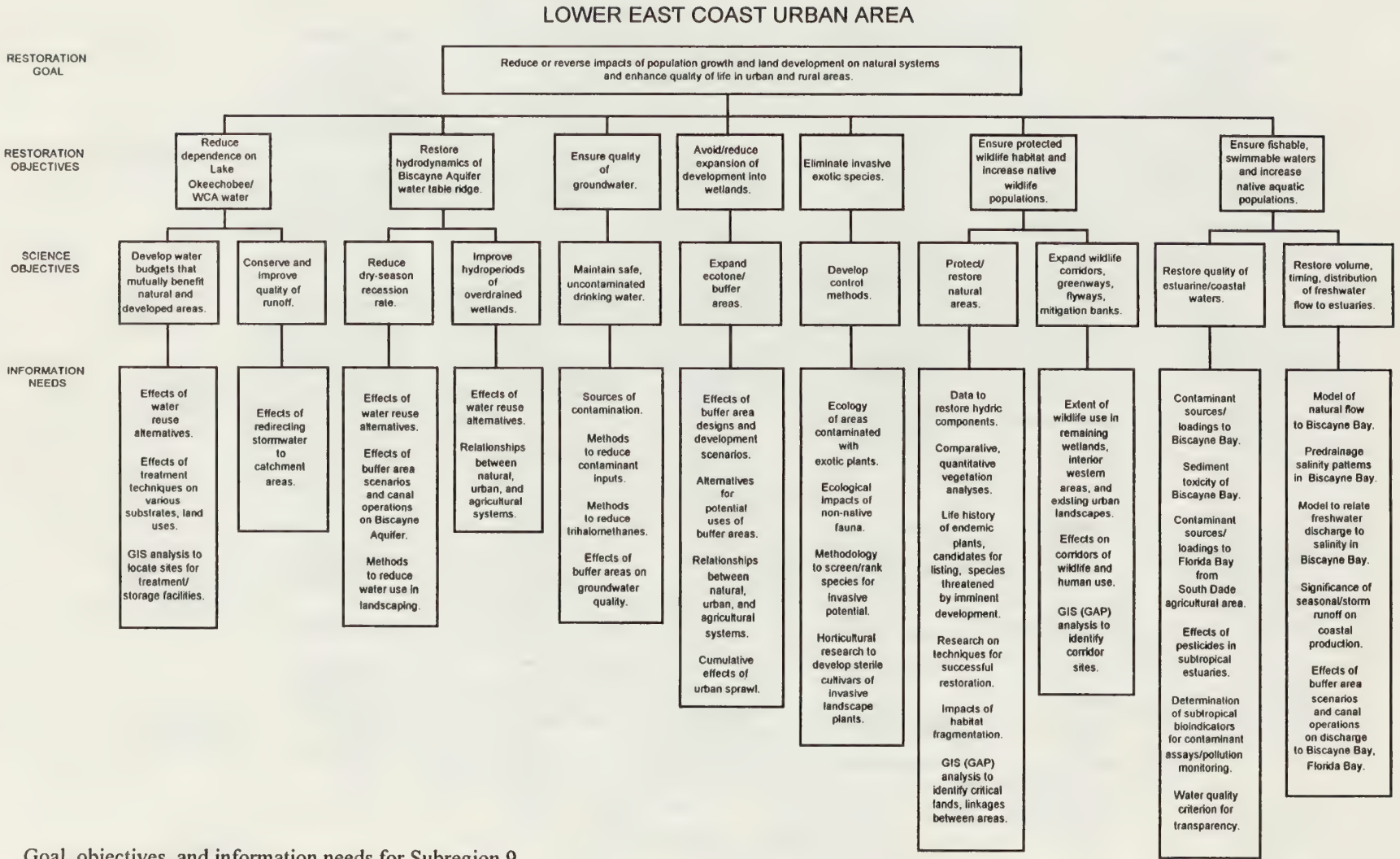
Goal, objectives, and information needs for Subregion 5.


BIG CYPRESS BASIN AND EVERGLADES NATIONAL PARK
RESTORATION GOAL
Restore structure and function of Everglades and Big Cypress ecosystems as nearly as possible to predrainage condition.
RESTORATION OBJECTIVES
Restore quantity, distribution, and timing of hydrologic flows and levels.
Restore (or maintain) water quality as close as possible to pristine conditions.
Restore natural vegetation and soil patterns and control by natural factors.
Increase long-term natural productivity of fish and invertebrate communities to maximum sustainable levels.
Increase populations of top predators to the maximum sustainable by the reduced natural landscape.
Reverse or arrest biodiversity declines in all landscapes, particularly uplands.
SCIENCE OBJECTIVES
Quantify and model flows and water levels within and between drainage basins.
Determine role of rainfall, climate, soils, vegetation, and water management.
Quantify and model factors controlling ambient water quality.
Define nutrient thresholds for major wetland communities.
Define contaminant thresholds for major wetland communities.
Determine historic and current patterns in soils and vegetation distribution and productivity (incl. periphyton).
Determine processes controlling soil formation and vegetation community development.
Quantify and model dynamics of productivity and composition of fish and invertebrate communities across landscapes and within wetland types.
Determine factors controlling foraging behavior, reproductive success, survival, and population size of key species.
Model relationships between changing landscape patterns and the loss of species, communities, and ecological heterogeneity.
INFORMATION NEEDS
Spatial distribution of surface and groundwater.
Aquifer and canal interactions.
Storm and drought effects on flow.
Elevation data.
Role of ET.
Soil infiltration rates.
Storage capacity.
Long-term responses of key plant and animal communities to P, N, and other nutrients under varying conditions.
Fates and pathways of nutrients and contaminants.
Models for simulating and predicting ecosystem responses to water quality alterations.
Conceptual reconstruction of vegetation patterns and soil changes over past 75 years.
Role of storms, drought, fire, and exotics in structuring vegetation communities and forming soils.
Food-web relationships.
Life histories of key species.
Competitive interactions.
Biocontaminant trends.
Climatic impacts on productivity and population size.
Landscape scale relationships among predators and prey, nesting patterns, reproduction, productivity, hydrologic conditions.
Alligator population dynamics among wetland types.
Hydrologic restoration effects on deer, panther, snail kite, Cape Sable sparrow, feral hog.
Critical factors controlling population size and distribution of endemic upland plant species and pineland vertebrates.
Habitat modification and management strategies for enhancing and restoring decimated populations.
Role of long-term change such as sea-level rise and human population growth on habitat diversity.

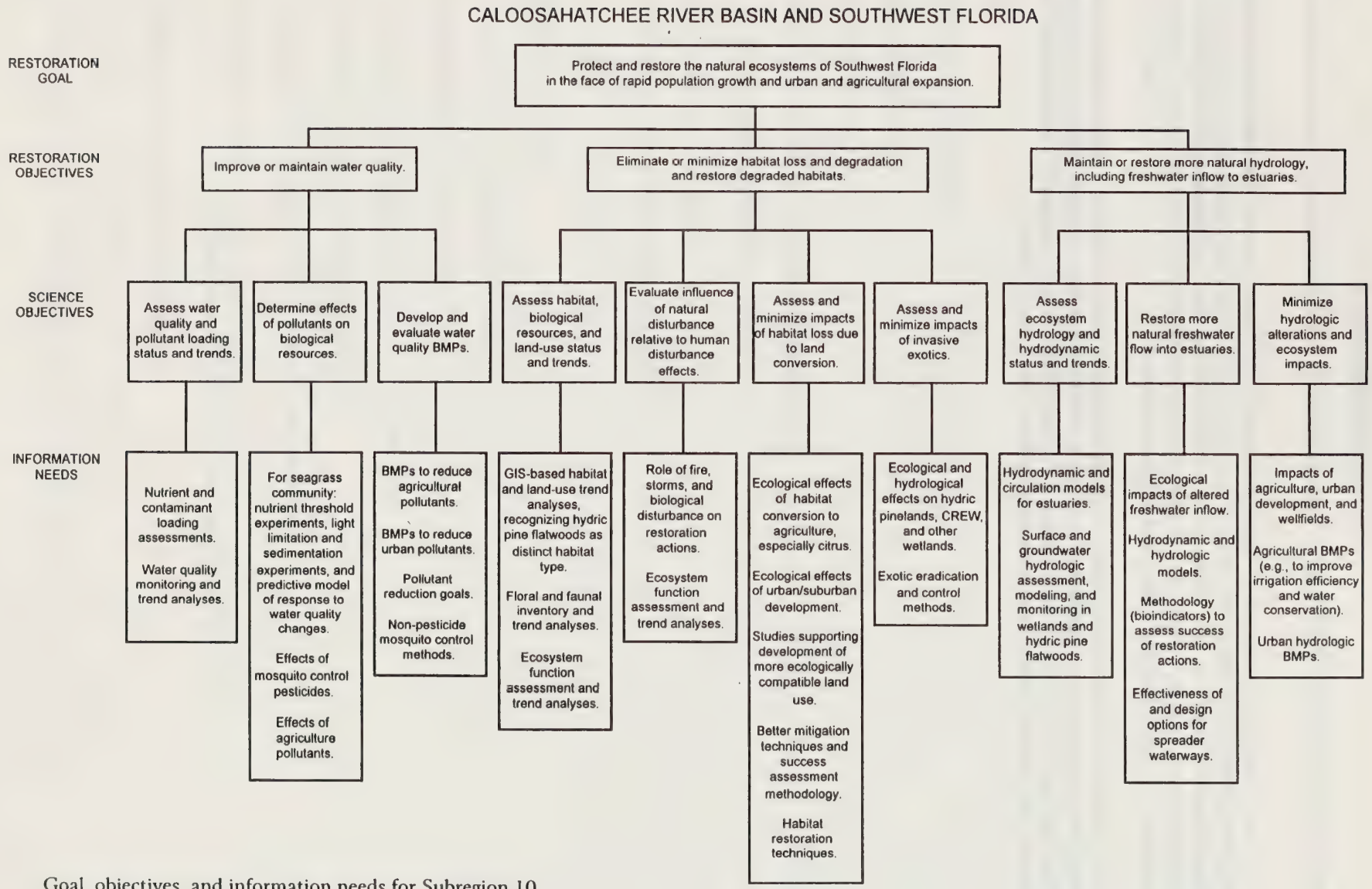
Goal, objectives, and information needs for Subregions 6 and 7.


SOUTHERN COASTAL AREAS
RESTORATION GOAL
Restore naturally functioning ecosystems that allow for long-term sustainable use and resource conservation.
RESTORATION OBJECTIVES
Restore water budgets, circulation dynamics, and salinity.
Restore water quality.
Restore seagrass, mangrove, and hardbottom habitats.
Preserve upland natural areas.
Restore wildlife resources.
SCIENCE OBJECTIVES
Develop information on factors that influence salinity, currents, and exchange rates.
Determine sources, sinks, quantities, qualities, and effects of "external" inputs.
Determine environmental variables that dictate distribution and condition of seagrass, mangrove, sponge, and coral habitats.
Protect natural areas. Expand wildlife corridors, flyways, and greenways.
Increase populations of protected and other native species.
Determine impacts of changes in habitat and environmental conditions on recruitment, growth, and survival.
INFORMATION NEEDS
Historical relationship of surface and groundwater flows through the Everglades, flow restriction through Keys channels, and Florida Bay salinity.
Effects of climate extremes on accumulation of sediments, nutrients, and organic matter in Florida Bay.
Effects of increased water residence time in Florida Bay caused by restricted Keys channel flow, shoaling, and reduced freshwater inflows.
Quantitative data on inputs and outputs for nutrient budget.
Nutrient exchange rates between sediment, water column, and plants.
Controls on magnitude and flux directions.
Phytoplankton, macroalgal, and coral nutrient assimilation rates.
Sources, quantities, and effects of toxic pollutants.
Cause of turbidity in Florida Bay and relation to water quality.
Principal environmental factors that explain observed distribution and recent die-off of seagrasses, corals, sponges, and mangroves.
Critical habitat.
Linkages between upland, coastal, and reef habitat.
Impacts of fragmentation on populations and processes.
Impacts of fragmentation.
Data necessary for recovery of endangered and threatened species.
Relationship of recruitment to habitat changes and distribution in estuaries and reef tract.
Relationship between altered conditions and growth and survival.
Relationship between habitat degradation/loss and fisheries productivity.
Relationship between Florida Bay habitat changes and changes in coral reefs and southern coastal areas.

Goal, objectives, and information needs for Subregion 8.


LOWER EAST COAST URBAN AREA
RESTORATION GOAL
Reduce or reverse impacts of population growth and land development on natural systems and enhance quality of life in urban and rural areas.
RESTORATION OBJECTIVES
Reduce dependence on Lake Okeechobee/ WCA water
Restore hydrodynamics of Biscayne Aquifer water table ridge.
Ensure quality of groundwater.
Avoid/reduce expansion of development into wetlands.
Eliminate invasive exotic species.
Ensure protected wildlife habitat and increase native wildlife populations.
Ensure fishable, swimmable waters and increase native aquatic populations.
SCIENCE OBJECTIVES
Develop water budgets that mutually benefit natural and developed areas.
Conserve and improve quality of runoff.
Reduce dry-season recession rate.
Improve hydroperiods of overdrained wetlands.
Maintain safe, uncontaminated drinking water.
Expand ecotone/ buffer areas.
Develop control methods.
Protect/ restore natural areas.
Expand wildlife corridors, greenways, flyways, mitigation banks.
Restore quality of estuarine/coastal waters.
Restore volume, timing, distribution of freshwater flow to estuaries.
INFORMATION NEEDS
Effects of water reuse alternatives.
Effects of treatment techniques on various substrates, land uses.
GIS analysis to locate sites for treatment/ storage facilities.
Effects of redirecting stormwater to catchment areas.
Effects of water reuse alternatives.
Effects of buffer area scenarios and canal operations on Biscayne Aquifer.
Methods to reduce water use in landscaping.
Effects of water reuse alternatives.
Relationships between natural, urban, and agricultural systems.
Sources of contamination.
Methods to reduce contaminant inputs.
Methods to reduce trihalomethanes.
Effects of buffer areas on groundwater quality.
Effects of buffer area designs and development scenarios.
Alternatives for potential uses of buffer areas.
Relationships between natural, urban, and agricultural systems.
Cumulative effects of urban sprawl.
Ecology of areas contaminated with exotic plants.
Ecological impacts of non-native fauna.
Methodology to screen/rank species for invasive potential.
Horticultural research to develop sterile cultivars of invasive landscape plants.
Data to restore hydric components.
Comparative, quantitative vegetation analyses.
Life history of endemic plants, candidates for listing, species threatened by imminent development.
Research on techniques for successful restoration.
Impacts of habitat fragmentation.
GIS (GAP) analysis to identify critical lands, linkages between areas.
Extent of wildlife use in remaining wetlands, interior western areas, and existing urban landscapes.
Effects on corridors of wildlife and human use.
GIS (GAP) analysis to identify corridor sites.
Contaminant sources/ loadings to Biscayne Bay.
Sediment toxicity of Biscayne Bay.
Contaminant sources/ loadings to Florida Bay from South Dade agricultural area.
Effects of pesticides in subtropical estuaries.
Determination of subtropical bioindicators for contaminant assays/pollution monitoring.
Water quality criterion for transparency.
Model of natural flow to Biscayne Bay.
Predrainage salinity patterns in Biscayne Bay.
Model to relate freshwater discharge to salinity in Biscayne Bay.
Significance of seasonal/storm runoff on coastal production.
Effects of buffer area scenarios and canal operations on discharge to Biscayne Bay, Florida Bay.

Goal, objectives, and information needs for Subregion 9.


CALOOSAHATCHEE RIVER BASIN AND SOUTHWEST FLORIDA
RESTORATION GOAL
Protect and restore the natural ecosystems of Southwest Florida in the face of rapid population growth and urban and agricultural expansion.
RESTORATION OBJECTIVES
Improve or maintain water quality.
Eliminate or minimize habitat loss and degradation and restore degraded habitats.
Maintain or restore more natural hydrology, including freshwater inflow to estuaries.
SCIENCE OBJECTIVES
Assess water quality and pollutant loading status and trends.
Determine effects of pollutants on biological resources.
Develop and evaluate water quality BMPs.
Assess habitat, biological resources, and land-use status and trends.
Evaluate influence of natural disturbance relative to human disturbance effects.
Assess and minimize impacts of habitat loss due to land conversion.
Assess and minimize impacts of invasive exotics.
Assess ecosystem hydrology and hydrodynamic status and trends.
Restore more natural freshwater flow into estuaries.
Minimize hydrologic alterations and ecosystem impacts.
INFORMATION NEEDS
Nutrient and contaminant loading assessments.
Water quality monitoring and trend analyses.
For seagrass community: nutrient threshold experiments, light limitation and sedimentation experiments, and predictive model of response to water quality changes.
Effects of mosquito control pesticides.
Effects of agriculture pollutants.
BMPs to reduce agricultural pollutants.
BMPs to reduce urban pollutants.
Pollutant reduction goals.
Non-pesticide mosquito control methods.
GIS-based habitat and land-use trend analyses, recognizing hydric pine flatwoods as distinct habitat type.
Floral and faunal inventory and trend analyses.
Ecosystem function assessment and trend analyses.
Role of fire, storms, and biological disturbance on restoration actions.
Ecosystem function assessment and trend analyses.
Ecological effects of habitat conversion to agriculture, especially citrus.
Ecological effects of urban/suburban development.
Studies supporting development of more ecologically compatible land use.
Better mitigation techniques and success assessment methodology.
Habitat restoration techniques.
Ecological and hydrological effects on hydric pinelands, CREW, and other wetlands.
Exotic eradication and control methods.
Hydrodynamic and circulation models for estuaries.
Surface and groundwater hydrologic assessment, modeling, and monitoring in wetlands and hydric pine flatwoods.
Ecological impacts of altered freshwater inflow.
Hydrodynamic and hydrologic models.
Methodology (bioindicators) to assess success of restoration actions.
Effectiveness of and design options for spreader waterways.
Impacts of agriculture, urban development, and wellfields.
Agricultural BMPs (e.g., to improve irrigation efficiency and water conservation).
Urban hydrologic BMPs.

Goal, objectives, and information needs for Subregion 10.

ACKNOWLEDGMENTS

Many scientists and resource managers throughout South Florida provided information for this report and participated in workshops leading to its publication. These included numerous representatives of State, county, and municipal agencies, as well as universities and research institutions, who contributed substantially to development of many sections of the report. Many of these persons also reviewed and commented on drafts of various chapters. We thank all who contributed information and helpful suggestions.

We also wish to thank those outside the Science Subgroup who graciously provided assistance in generating graphics files for this report: Jennifer Bexley of the FDEP Florida Marine Research Institute, Larry Massey and Anthony Martinez of the NOAA/NMFS Southeast Fisheries Science Center, Leonard Pearlstine of the University of Florida, and Barbara Welch of the South Florida Water Management District.

CONTENTS

EXECUTIVE SUMMARY iii

ACKNOWLEDGMENTS xx

LIST OF FIGURES xxii

LIST OF TABLES xxiii

LIST OF ACRONYMS AND ABBREVIATIONS xxiv

PREFACE xxviii

THE REGIONAL ECOSYSTEM 1

SCIENTIFIC APPROACH 6

REGION-WIDE TOPICS

THREATENED AND ENDANGERED SPECIES 25

HARMFUL NONINDIGENOUS SPECIES 38

MERCURY IN THE ECOSYSTEM 49

PESTICIDES AND URBAN CONTAMINANTS 72

MODELS 79

SUBREGION CHAPTERS

SUBREGION 1: Kissimmee River Basin 112

SUBREGION 2: Lake Okeechobee 146

SUBREGION 3: Upper East Coast-St. Lucie River Area 158

SUBREGION 4: Everglades Agricultural Area 194

SUBREGION 5: Everglades Water Conservation Areas 247

SUBREGIONS 6 and 7: Big Cypress Basin and Everglades National Park (Mainland Portion) 271

SUBREGION 8: Southern Coastal Areas 307

SUBREGION 9: Lower East Coast Urban Area 365

SUBREGION 10: Caloosahatchee River Basin and Southwest Florida 470

LIST OF FIGURES

(List does not include figures that are part of attached appendices.)

Figure 1. South Florida subregions 4

Figure 2. South Florida region-wide goal, objectives, and information needs 9

Figure 3. Goal, objectives, and information needs for efforts on threatened and endangered species 27

Figure 4. Goal, objectives, and information needs for efforts on nonindigenous species 44

Figure 5. Goal, objectives, and information needs for efforts on mercury 51

Figure 6. Goal, objectives, and information needs for efforts on pesticides and urban contaminants 74

Figure 7. Pathways of model interdependencies 80

Figure 8. Goal, objectives, and information needs for modeling efforts 81

Figure 9. Goal, objectives, and information needs for Subregion 1 113

Figure 10. Goal, objectives, and information needs for Subregion 2 150

Figure 11. Goal, objectives, and information needs for Subregion 3 162

Figure 12. Theoretical subsidence scenarios in the EAA using the equation of Stephens et al. (1984) 205

Figure 13. Goal, objectives, and information needs for Subregion 4 219

Figure 14. Goal, objectives, and information needs for Subregion 5 250

Figure 15. Goal, objectives, and information needs for Subregions 6 and 7 273

Figure 16. Goal, objectives, and information needs for Subregion 8 308

Figure 17. Areas included under science and management plans for Subregion 8 311

Figure 18. Goal, objectives, and information needs for Subregion 9 388

Figure 19. Goal, objectives, and information needs for Subregion 10 481

LIST OF TABLES

(List does not include tables that are part of attached appendices.)

Table 1. Proposed special studies 15

Table 2. Proposed studies on protected species and species of special concern 16

Table 3. Studies that will help develop an information base for assessment indicators and models 17

Table 4. Fallow and successive sugarcane planting systems 203

Table 5. Phosphorus fertilizer recommendations for crops grown on Histosols in the EAA across a wide range of soil-test-P index levels 206

Table 6. Science projects funded by the NPS Hurricane Andrew Program (1993-96) 281

Table 7. Status of endangered and threatened species in Subregion 8 310

LIST OF ACRONYMS AND ABBREVIATIONS

ADID	Advance Identification (EPA)
AIW	Atlantic Intracoastal Waterway
AOML	Atlantic Oceanographic and Meteorological Laboratory (NOAA)
APHIS	Animal and Plant Health Inspection Service (USDA)
AREAL	Atmospheric Research and Exposure Assessment Laboratory (EPA)
ARPS	Advanced Regional Prediction System
ARS	Agricultural Research Service (USDA)
ASAE	American Society of Agricultural Engineers
ATLSS	Across-Trophic-Level System Simulation
AWRA	American Water Resources Association
BAF	bioaccumulation factor
BBSWQMP	Biscayne Bay Routine Surface Water Quality Monitoring Program (Dade County)
BC	Big Cypress
BCF	bioconcentration factor
BCNP	Big Cypress National Preserve
BCPC	Broward County Planning Council
BIA	Bureau of Indian Affairs (DOI)
BMPs	best management practices
BNP	Biscayne National Park
BRD	Biological Resources Division (USGS)
CARL	Conservation and Recreation Lands
C-CAP	Coastal Change Analysis Program (NOAA)
CCMP	Comprehensive Conservation and Management Plan
CDM	Camp, Dresser, and McKee
CMEA	Center for Marine and Environmental Analyses (UM)
COE	U.S. Army Corps of Engineers
COVER	Colloqui of Vegetation Everglades Research
CREW	Corkscrew Regional Ecosystem Watershed
CSA	Continental Shelf Associates
C&SF FCD	Central and Southern Florida Flood Control District
C&SF Project	Central and Southern Florida Project for Flood Control and Other Purposes (COE)
CWA	Clean Water Act
DERM	Department of Environmental Resources Management (Dade County or Palm Beach County)
DIMS	Data and Information Management Strategy
DNRP	Department of Natural Resource Protection (Broward County)
DO	dissolved oxygen
DOC	dissolved organic carbon
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
DSDL	Distributed Spatial Data Library (USGS)
EAA	Everglades Agricultural Area
ECFRPC	East Central Florida Regional Planning Council
EELAP	Environmentally Endangered Lands Acquisition Program (Dade County)
EFA	Everglades Forever Act
ELM	Everglades Landscape Model
EMAP	Environmental Monitoring and Assessment Program (EPA)

ENP	Everglades National Park
ENR	Everglades Nutrient Removal Project
EPA	U.S. Environmental Protection Agency
EPD	Environmental Protection District
EPD	Everglades Protection District
ERD	Ecosystems Research Division (EPA)
EREC	Everglades Research and Education Center (IFAS)
ERP	Everglades Research Plan
ESA	Endangered Species Act
ESL	Environmentally Sensitive Land (Broward County and Palm Beach County)
ET	evapotranspiration
FAA	Federal Aviation Administration (DOT)
FASS	Florida Agricultural Statistics Service (FDACS)
FAU	Florida Atlantic University
FCD	Flood Control District
FCMP	Florida Coastal Management Program (FDCA)
FCREPA	Florida Committee on Rare and Endangered Plants and Animals
FDACS	Florida Department of Agriculture and Consumer Services
FDCA	Florida Department of Community Affairs
FDEP	Florida Department of Environmental Protection
FDER	Florida Department of Environmental Regulation
FDHRS	Florida Department of Health and Rehabilitative Services
FDM	Feature Design Memorandum
FDNR	Florida Department of Natural Resources
FDOF	Florida Division of Forestry (FDACS)
FDOT	Florida Department of Transportation
FECR	Florida East Coast Railway
FGDC	Federal Geographic Data Committee
FGETS	Food and Gill Exchange of Toxic Substances model
FGFWFC	Florida Game and Fresh Water Fish Commission
FHWA	Federal Highway Administration (DOT)
FIO	Florida Institute of Oceanography
FIU	Florida International University
FKNMS	Florida Keys National Marine Sanctuary
FLEPPC	Florida Exotic Pest Plant Council
FMRI	Florida Marine Research Institute (FDEP)
FNAI	Florida Natural Areas Inventory
FOF	1000 Friends of Florida
FPL	Florida Power & Light Company
FPOM	fine particulate organic matter
FSCL	Florida Sugar Cane League, Inc.
FSU	Florida State University
FWQA	Federal Water Quality Administration
FWS	U.S. Fish and Wildlife Service (DOI)
GAP	Gap Analysis Program
GIS	Geographic Information System
GPO	U.S. Government Printing Office (Superintendent of Documents)
GPS	Global Positioning System
Hg	mercury
HMG	Hydrologic Modeling Group (COE)

ICSB	International Consortium of Sugarcane Biotechnologists
IFAS	Institute of Food and Agricultural Sciences (University of Florida)
IPM	integrated pest management
IRL	Indian River Lagoon
IRLNEP	Indian River Lagoon National Estuary Program
KRRP	Kissimmee River Research Plan
LEC	Lower East Coast
LORP	Lake Okeechobee Research Plan
LOTAC-I	Lake Okeechobee Technical Advisory Committee
LOTAC-II	Lake Okeechobee Technical Advisory Council
LSU	Louisiana State University
MCL	maximum contaminant level
MCM	Mercury Cycling Model
MeHg	methyl mercury
MTF	Melaleuca Task Force
N	nitrogen
NAS	National Audubon Society
NAWQA	National Water-Quality Assessment Program (USGS)
NBS	National Biological Service (DOI) (NBS is now the Biological Resources Division of USGS)
NEP	National Estuary Program
NERR	National Estuarine Research Reserve
NESDIS	National Environmental Satellite, Data, and Information Service (NOAA)
NEXRAD	Next Generation Radar
NMFS	National Marine Fisheries Service (NOAA)
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service (NOAA)
NPDES	National Pollutant Discharge Elimination System
NPS	National Park Service (DOI)
NRCS	Natural Resources Conservation Service (USDA)
NSM	Natural System Model
NWI	National Wetlands Inventory
NWR	National Wildlife Refuge
NWS	National Weather Service (NOAA)
OAR	Office of Oceanic and Atmospheric Research (NOAA)
ORNL	Oak Ridge National Laboratory
OTA	Office of Technology Assessment (U.S. Congress)
P	phosphorus
PAH	polycyclic aromatic hydrocarbon
PAR	photosynthetically active radiation
PCB	polychlorinated biphenyl
PRD	Parks and Recreation Division (Broward County)
PRD	Park and Recreation Department (Dade County)
PVA	Population Viability Analysis
RADM	Regional Atmospheric Deposition Model
RAF	Regional Attenuation Facility
RELMAP	REgional Lagrangian Model of Air Pollution
R-EMAP	Regional Environmental Monitoring and Assessment Program (EPA)
RFLP	restriction fragment length polymorphism
RSMAS	Rosenstiel School of Marine and Atmospheric Science (UM)

SAF	Small Attenuation Facility
SAV	submerged aquatic vegetation
SCS	Soil Conservation Service (USDA)
SEFCAR	Southeast Florida and Caribbean Recruitment Program
SFARPS	South Florida Advanced Regional Prediction System
SFERTF	South Florida Ecosystem Restoration Task Force
SFRC	South Florida Research Center (NPS)
SFRPC	South Florida Regional Planning Council
SFRRM	South Florida Regional Routing Model
SFRSM	South Florida Regional Simulation Model
SFWMD	South Florida Water Management District
SFWMM	South Florida Water Management Model
SJRWMD	St. Johns River Water Management District
SOR	Save Our Rivers
SRA	State Recreation Area
SSC	Species of Special Concern
SSG	Science Subgroup
SRF	Systematic Reconnaissance Flight
STA	Stormwater Treatment Area
SWFWMD	Southwest Florida Water Management District
SWIM	Surface Water Improvement and Management
TAS	Tropical Audubon Society
TLCM	Toxics Linear Chemistry Model
THM	trihalomethane
UF	University of Florida
UM	University of Miami
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey (DOI)
UT	University of Tennessee
WASAD	Water and Sewer Authority Department (Miami-Dade)
WCA	Water Conservation Area
WFS	West Florida Shelf
WWIPA	West Wellfield Interim Protection Area (Dade County)

PREFACE

The Interagency Task Force, in its Agreement on South Florida Ecosystem Restoration (September 23, 1993), observed that the restoration effort needs to be founded on scientific information and mandated that the effort take an ecosystem approach. This document is structured to provide information in support of the ecosystem approach. It is the first step in development of an ecosystem-based South Florida Integrated Science Plan that includes monitoring, modeling, and empirical studies.

An **ecosystem** is the entire dynamic complex of interrelating plants, animals, and microorganisms at a location and their abiotic environment. The ecosystem includes humans and their influences, when present. **Ecosystem management** recognizes and attempts to conserve the structure of natural ecosystems as embodied in species composition, food webs, and major functions of ecosystems, such as primary productivity and mineral cycling. It addresses the need to sustain viable populations of multiple species over the long term. Ecosystem management extends beyond management of natural communities to address the balancing of human needs with resource protection. Grumbine (1994) lists the following mandates of ecosystem management: 1) maintain viable populations of all native species *in situ*; 2) represent within protected areas all native ecosystem types across their natural range of variation; 3) maintain evolutionary and ecological processes (e.g., disturbance regimes, hydrologic processes, nutrient cycles); 4) manage over long enough periods of time to maintain the evolutionary potential of species and ecosystems; and 5) accommodate human use and occupancy within these constraints. He refers to several dominant themes of ecosystem management, paraphrased as follows:

- Ecosystem management mandates examining a problem at more than one hierarchial scale (genes, species, populations, ecosystems, landscapes) and seeking connections between all levels. A major tenet of ecosystem management is conservation of ecological integrity. Ecological integrity is conserved by protecting native diversity and the ecological patterns and processes that maintain diversity. This is done by maintaining viable populations of native species, allowing natural disturbance regimes, reintroducing native extirpated species, and preserving ecosystems across natural ranges of variation.

- Ecosystem management requires new research and data collection (i.e., habitat inventory classification, disturbance regime dynamics, baseline species and population assessment, as well as better management and use of existing information). Managers must track the results of their actions so success or failure can be evaluated quantitatively. Monitoring creates an ongoing feedback loop of useful information.

- **Adaptive management** is part of the ecosystem approach. It assumes scientific knowledge is provisional and focuses on management as a learning process for continuous experiment in which incorporating results of previous actions allows managers to remain flexible and adapt to uncertainty.

- Humans are part of the ecosystem and cannot be separated from it in ecosystem management. Humans exert fundamental influences on ecological patterns and processes and are in turn affected by them. Human values play a dominant role in ecosystem management goals.

- Management requires working across administrative political boundaries to address issues within ecological boundaries. Using ecological boundaries requires cooperation between federal, state, and local management agencies, as well as private parties. Managers must learn to work together and integrate conflicting legal mandates and management goals. Implementing ecosystem management requires changes in the structure of land management agencies and the way they operate. These may range from the simple (forming an interagency committee) to the complex (changing professional norms, alternating power relationships).

The Science Subgroup was formed as a science advisory group to provide scientific information to the South Florida Interagency Management and Coordination Working Group. The following responsibilities, not listed

in priority order, were identified in the Science Subgroup Charter (September 21, 1993) under the Interagency Agreement on South Florida Ecosystem Restoration:

- Recommend South Florida Ecosystem boundaries.
- Identify key information gaps and plan an integrated science program, revising the plan periodically.
- Develop a process to coordinate science efforts.
- Evaluate models.
- Develop a monitoring plan.
- Develop a computerized guide to all relevant data sets.

The Science Subgroup will not accomplish these alone or in isolation. In fact, the Science Subgroup may act mainly in an oversight capacity in accomplishing some of the above tasks. Special committees made up of scientists appointed by various agencies and governments will do various aspects of the work.

This Scientific Information Needs report is the first step in development of the Integrated Science Plan to support region-wide South Florida Ecosystem Restoration. The Science Subgroup decided that organizing the information needs into a document that could be critically reviewed was a necessary preamble to development of a coordinated science plan. The draft report was circulated for comment by science peers, managers, and the public, and we have attempted to incorporate all relevant input. This revised document identifies gaps and sets priorities in planning an integrated interagency and intergovernmental science program. The framework of the Science Plan will be strategic questions that relate to restoration objectives and an assessment protocol that integrates modeling, monitoring, and special restoration support studies.

The first two sections of this document are: 1) a brief description of the South Florida Ecosystem that addresses issues of sustainability and 2) a description of the approach needed to obtain the scientific basis for restoration, as well as the issues involved in applying this approach. Next are individual chapters on nonindigenous species, endangered species, mercury, pesticides and other contaminants, and modeling (hydrologic, hydrodynamic, meteorologic, and ecologic). These special topics are discussed here from a region-wide, holistic perspective; they are not summaries of information from the subsequent subregion chapters. The major portion of the report is divided into chapters that detail the science needs of each of the subregions identified in the 1993 Science Subgroup report, modified to include a Subregion 10. Subregions 6 and 7 are combined into a single chapter because of similar science needs and restoration goals. Discussion of Indian lands (Seminole and Miccosukee Tribes) is included in the chapter on Subregions 6 and 7 since all of the Seminole Big Cypress Reservation and one-third of the Miccosukee Reservation are contained in the Big Cypress Basin. The subregion chapters were developed by convening workshops of experts and gaining consensus regarding information needs or by obtaining information from knowledgeable experts on an individual basis. The information in each subregion chapter is generally organized into sections on introduction, background, major issues, objectives, information needs, and bibliography (which may include many references in addition to those cited in the text). For some subregions, this format was modified to accommodate special information. For example, science plans are already in place for Subregion 1 (Kissimmee River), Subregion 2 (Lake Okeechobee), and some areas of Subregion 8 (e.g., Florida Bay), and these chapters integrate the existing plans into the region-wide restoration initiative.

BIBLIOGRAPHY

Grumbine, R.E. 1994. What is ecosystem management? Conservation Biology 8:27-38.

Interagency Task Force. 1993. Interagency agreement on South Florida Ecosystem Restoration. September 23, 1993.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

THE REGIONAL ECOSYSTEM

INTRODUCTION

The South Florida Ecosystem, as defined by the Science Subgroup (SSG 1993), covers the area within the jurisdiction of the South Florida Water Management District. It includes coastal waters and islands, including Florida Bay, Biscayne Bay, and other estuaries and the Florida Keys and reef tract to the Dry Tortugas. The South Florida Ecosystem encompasses an area of approximately 28,000 km^2 (10,800 mi^2) comprising at least 11 major physiographic provinces. These include the Kissimmee River Valley, Lake Okeechobee, the Immokalee Rise, the Big Cypress, the Everglades, Florida Bay, the Atlantic Coastal Ridge, Biscayne Bay, the Florida Keys, the Florida reef tract, and nearshore coastal waters.

BACKGROUND

South Florida is a heterogeneous system of wetlands, uplands, and coastal and marine areas, dominated by the watersheds of the Kissimmee River, Lake Okeechobee, and the Everglades. Prior to drainage, wetlands covered most of central and southern Florida. Wetland landscapes included swamp forests; sawgrass plains; mosaics of sawgrass, tree islands, and ponds; marl-forming prairies dominated by periphyton; wet prairies dominated by *Eleocharis* and *Nymphaea*; freshwater marshes; saltwater marshes; cypress strands; and a vast lake-river system draining into Lake Okeechobee. Elevated areas that seldom were inundated supported pine flatwoods, pine rocklands, scrub, tropical hardwood hammocks, and xeric hammocks dominated by oaks. The natural seascapes of South Florida consisted of riverine and fringe mangrove forests, beaches and dunes, seagrass beds, intertidal flats, mud banks, hardbottom communities, coral reefs, and open, inshore shallows. These habitats were interconnected on an extremely low topographic gradient of 2.8 cm/km (1.8 in/mi) in which elevations ranged from about 6 m (20 ft) at Lake Okeechobee to below sea level at Florida Bay.

The biological abundance and diversity these habitats once supported were maintained by the complex annual and long-term hydrologic patterns of the natural system, as expressed in wet-dry cycles, rates of expansion and contraction of water area, surface water and water depth patterns, annual hydroperiods, flow volumes, and, at the coast, salinity and mixing patterns. Superimposed over the periodic changes were sporadic events such as storms, fires, and freezes, which helped to establish and maintain habitat heterogeneity. Productivity of the predrainage wetlands of South Florida was dependent on:

- **Dynamic hydrologic storage and sheetflow.** Contributing to dynamic storage were the very shallow elevation gradient, vast expanses of emergent vegetation, thick peat substrates, sand hills, and highly permeable limestones. Water masses were constantly progressing downslope but so slowly that, in effect, water was banked during one season to use in another. Transport varied between structural elements from on the order of months to years. Throughout the system, groundwater seepage driven by hydraulic gradients provided the base flow of creeks, rivers, and possibly even surface runoff across the mangrove zone. The extended hydroperiods of the natural system depended more on the large dynamic storage capacity and delayed flow-through than on the immediate effects of rainfall. Because of the dynamic storage and slow rate of water flow throughout the natural system, wet season rainfall kept the wetlands flooded and maintained freshwater flow to the estuaries well into the dry season. This carry-over effect was so great that a year of high rainfall maintained surface water in wetlands and freshwater flow to estuaries even into one (Walters et al. 1992; Fennema et al. 1994) or more (Browder 1976) subsequent drought years. The dynamic storage made wetlands and estuaries less vulnerable to South Florida's spatially and temporally variable rainfall.

- **Large spatial scale.** The vastness of the predrainage wetland made it possible for the natural ecosystem to support genetically viable numbers and subpopulations of species with large feeding ranges or narrow habitat requirements, provide the aquatic production to support large numbers of higher vertebrate animals in a naturally nutrient-poor environment, and sustain habitat diversity through natural disturbance (DeAngelis 1994; DeAngelis

and White 1994). Population resiliency was undoubtedly proportional to the extent of these wetlands because habitat diversity, number of seasonal refugia, and number of dispersal options are proportional to wetland area. The same is true of other habitat types, such as the pinelands, which extended for vast distances.

- **Heterogeneity in habitat.** Habitat heterogeneity was a major contributor to biotic diversity and the persistence of populations (DeAngelis 1994; DeAngelis and White 1994). The vegetative landscape resulting from the vast, low-relief, low-gradient landform was a diverse mosaic of plant communities that varied in extent from patches on the order of tens of meters to areas approaching physiographic provinces. Heterogeneity was maintained by micro-topographic features, small-scale climatic variation, and natural disturbances such as freezes, fire, and storms, acting on the large spatial scale (DeAngelis 1994). The mosaic of habitat types and water depths provided the spatial framework for production and survival of animals under a wide seasonal and annual range of hydrologic conditions.

South Florida is home to two federally recognized Indian tribes, the Seminoles and the Miccosukees, whose reservations are an integral part of the ecosystem. Native Americans have inhabited southern Florida for at least 10,000 years, predating formation of the "Everglades" by about 5000 years (Carr and Beriault 1984). The modern Seminoles and Miccosukees in the Everglades began establishing their populations (collectively as Seminoles) circa 1720 (Paige and Vanhorn 1982). The historical presence of Native Americans can be regarded as part of the natural ecosystem (Lodge 1994). The Miccosukee and Seminole Tribes of Florida became Federally recognized in 1962 and 1957, respectively, and their reservations became Federal trust lands to be held in trust for the tribes, their resources protected by the Federal Government. Today, approximately 462,000 acres of land in South Florida are considered Indian lands. This includes much of WCA 3A, which is perpetually leased by the State of Florida to the Miccosukee Tribe. The traditional and modern lifestyles of approximately 2500 tribal members are dependent on fulfillment of the Federal Government's trust responsibility to protect their lands, resources, and use rights.

MAJOR ISSUES

Water quality and water quantity problems for South Florida's natural systems, including the Everglades and estuaries, have resulted from man-made changes in the hydrologic system. These changes began before the turn of the century with dredging that channelized the Caloosahatchee River and connected it to Lake Okeechobee. With increasing population growth after 1900 came massive modification of the natural system. Changes in the hydrologic structure of South Florida culminated in creation and implementation of the C&SF Project in 1948. The enabling legislation gave the COE responsibility for construction and oversight of water management structures throughout the Kissimmee-Okeechobee-Everglades basin. In 1949, the State created the Central and Southern Florida Flood Control District, which has since become the SFWMD. Project purposes were: 1) flood control; 2) drainage; 3) water supply (municipal, industrial, and agricultural); 4) protection against salt water intrusion; 5) preservation of fish and wildlife resources in the Everglades; 6) water supply to ENP; and 7) recreation and navigation. Initial focus was on flood control, drainage, and water supply.

Flood control made possible massive land-use changes that decreased the land available for water storage and recharge. These land-use changes and associated population growth resulted in a three-part ecosystem consisting of an urban component, an agricultural component, and part of the original natural system that is largely undeveloped but still impacted by man. These three components are interconnected by the flow of energy and resources (Browder et al. undated; McPherson et al. 1976; Odum et al. 1993). A comprehensive discussion of the natural and altered systems of South Florida was presented by McPherson et al. (1976).

A rapidly expanding human population approaching 6 million has developed in South Florida, mainly in upland areas such as the Atlantic Coastal Ridge but also in wetlands. The South Florida Ecosystem (i.e., the SFWMD area) encompasses all or portions of 16 counties. The combined population of the counties included in entirety (Broward, Collier, Dade, Glades, Hendry, Lee, Martin, Monroe, Palm Beach, and St. Lucie) was 4.9 million in 1990 and estimated at 5.1 million in 1993. The population of counties partially included (Charlotte, Highlands, Okeechobee, Orange, Osceola, and Polk) was 1.4 million in 1990 and estimated at 1.5 million in 1993 (Bur. Econ. Bus. Res. 1994). Although much of the population of some of these boundary counties resides outside the defined area, it still impacts South Florida. For instance, the city of Orlando is outside the boundary, but it lies

just upstream of the head of the Kissimmee-Okeechobee-Everglades drainage. The large tourist area of Kissimmee-Walt Disney World is actually within the SFWMD boundary.

Most of the population of South Florida is concentrated along the Lower East Coast in Palm Beach, Broward, and Dade counties, the most heavily urbanized area in the state. With a combined population of 4.1 million people in 1990, these three counties are home to more than 30% of Florida residents. Dade County alone comprises almost 15% of the state's population. Dade, Broward, and Palm Beach counties are first, second, and third, respectively, in the state's population rankings. Collier County on the West Coast has been the fastest growing county in South Florida. Between 1970 and 1990, its population quadrupled from 38,000 to 152,000 (Bur. Econ. Bus. Res. 1994).

This expanding human presence, with all its needs and demands, has dramatically changed the South Florida Ecosystem. In addition to hydrologic alterations that have decreased the natural ability of the system to store water in wetlands, soils, and the aquifer, the expanding population has created an increased demand for water for both urban and agricultural uses. When wetlands are developed, demand for water is increased by new users while, at the same time, the supply of consistently available water is decreased by loss of places to temporarily store water. Other changes that have accompanied population growth and economic expansion are water quality and treatment problems, soil subsidence in the Everglades Agricultural Area, nutrient enrichment, pollution by contaminants, fragmentation of habitats and landscapes by urban development, loss of wetland areas and functions to development, altered fire regimes, declines in reef and estuarine resources, and invasion of parks and natural areas by many non-native plants and animals introduced into South Florida. By addressing these problems, restoration of the South Florida Ecosystem will support more sustainable economic opportunities while at the same time improve the sustainability of the natural ecosystem.

Quality of life in South Florida is strongly affected by the condition of its natural systems, which provide many benefits to agriculture and urban communities. These benefits include adequate supplies of clean water, clean air, aesthetically pleasing natural landscapes, natural controls on agricultural pests, and an interesting diversity of wildlife and fishery resources. If the natural systems are destroyed or reduced, their free services are diminished or lost (Browder et al. undated; McPherson et al. 1976).

Agriculture is a significant land use in South Florida. Major products include cattle, sugarcane, vegetables, citrus, tropical fruits, rice, sod, and ornamental plants. Much of the U.S. winter supply of vegetables such as tomatoes, green beans, peppers, and yellow squash is provided by South Florida agriculture. Some South Florida crops are not grown commercially anywhere else in the U.S. Recently, land conversion to citrus has increased substantially as a result of interregional movement of citrus farming from Central to Southwest Florida following several severe freezes in the mid-1980s.

The South Florida Ecosystem is nationally and internationally significant for its wildlife and fish. Tourism is a major industry in the Region, and much of the attraction is due to the remaining natural areas and their resources. Recreational fishing and diving are significant to the overall economy of South Florida, both directly and through their stimulation of tourism. For example, recreational activities and tourism account for 50% of the total employment in Monroe County, which consists of the Florida Keys and much of ENP. Recreational fishing contributes about $77 million to the economy per year, while diving contributes about $354 million to the Florida Keys alone. ENP (a designated World Heritage Site and Biosphere Reserve), BNP, and other scenic wetland areas are large tourist magnets, as are many State, county, and municipal lands maintained as parks and natural areas. The future of this segment of the tourism industry is directly tied to the condition of the South Florida Ecosystem. Clearly, ecosystem restoration means improvement in local quality of life and the regional economy.

A comprehensive discussion of the natural and altered systems of South Florida was presented by McPherson et al. (1976). The SSG (1993) described the defining characteristics of the South Florida Ecosystem and the problems that have resulted from hydrologic alterations and other anthropogenic changes. Nine geographic subregions were delineated, and restoration objectives were proposed for the Region as a whole and each of the subregions. For the present report, boundaries of the subregions were slightly modified and scientific information needs are presented for 10 subregions (Figure 1).

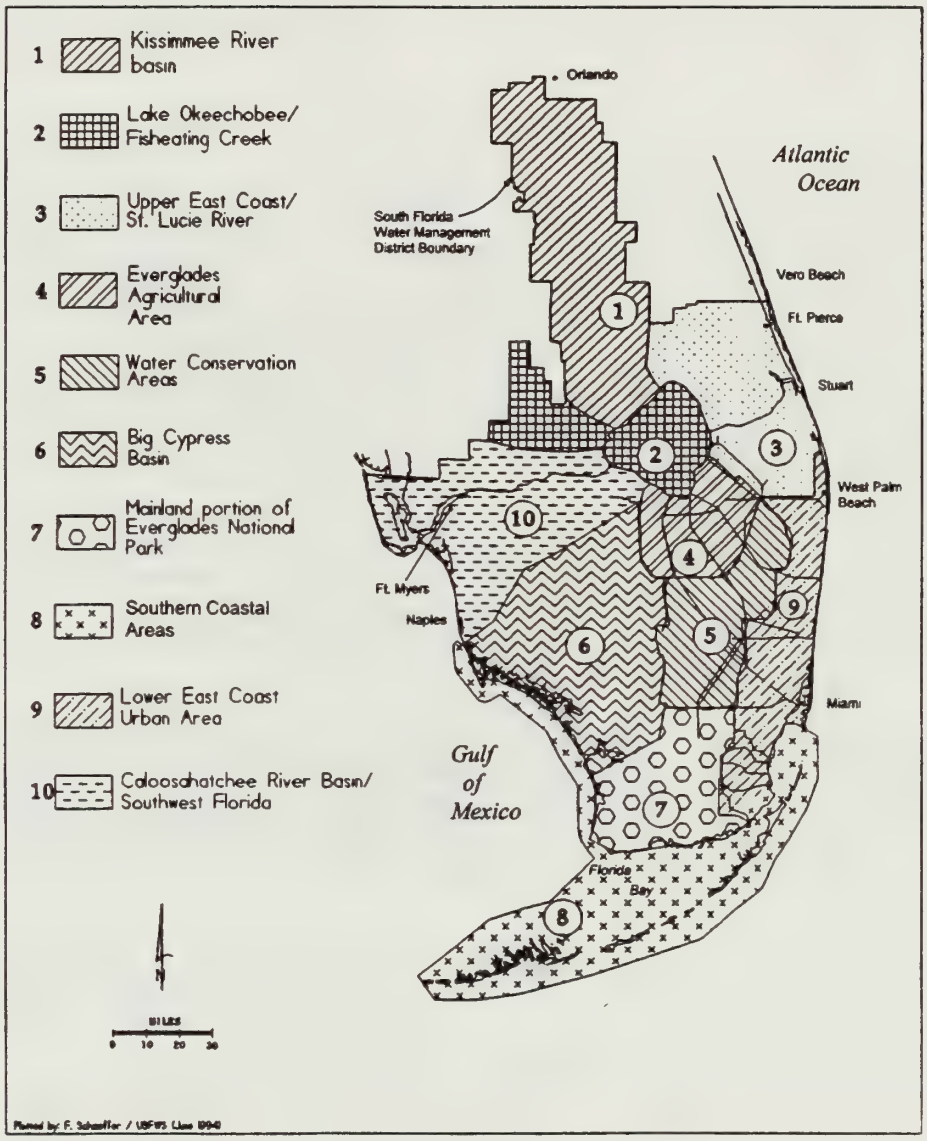


Figure 1. South Florida subregions.

GOAL

The overall goal of the restoration effort is to restore a sustainable South Florida Ecosystem that preserves the valued properties of South Florida's natural systems and supports productive agriculture-, fishery-, and tourist-based economies and a high quality of urban life. Sustainability means high natural productivity, human and ecosystem health, and resiliency to climatic extremes and catastrophic events. It also means long-term accommodation of needs of human systems, such as flood control, irrigation, and drinking water supply.

The scientific approach to accomplish this goal is presented in the following chapter.

BIBLIOGRAPHY

Browder, J.A. 1976. Water, wetlands, and wood storks. Ph.D. dissertation. UF, Gainesville, Florida.

Browder, J.A., C. Littlejohn, and D. Young. Undated. The South Florida study, South Florida: Seeking a Balance of Man and Nature. UF Center for Wetlands and Florida Bureau of Comprehensive Planning.

Bureau of Economic and Business Research, College of Business Administration, University of Florida. 1994. 1994 Florida Statistical Abstract. University Press of Florida, Gainesville, Florida.

Carr, R.S., and J.C. Beriault. 1984. Prehistoric man in southern Florida. Pages 1-9 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Memoir II, Miami Geological Society, Miami, Florida.

DeAngelis, D.L. 1994. Synthesis: spatial and temporal characteristics of the environment. Pages 307-322 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

DeAngelis, D.L., and P.S. White. 1994. Ecosystems as products of spatially and temporally varying driving forces, ecological processes, and landscapes: a theoretical perspective. Pages 9-28 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Fennema, R.J., C.J. Neidrauer, R.A. Johnson, W.A. Perkins, and T.K. MacVicar. 1994. A computer model to simulate natural South Florida hydrology. Pages 249-290 *in* S. M. Davis and J. C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Lodge, T.E. 1994. The Everglades Handbook. St. Lucie Press, Delray Beach, Florida.

McPherson, B.F., G.Y. Hendrix, H. Klein, and H.M. Tyus. 1976. The environment of South Florida, a summary report. Geological Survey Professional Paper 1011. GPO, Washington, D.C.

Odum, H.T., E.C. Odum, and M.T. Brown. 1993. Environment and Society in Florida. Draft, August 1993. Center for Environmental Policy, UF, Gainesville, Florida.

Paige, J.C., and L.F. Vanhorn. 1982. An ethnohistory of Big Cypress National Preserve, Florida. DOI, NPS.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Walters, C., L. Gunderson, and C.S. Holling. 1992. Experimental policies for water management in the Everglades. Ecological Applications 2:189-202.

SCIENTIFIC APPROACH

INTRODUCTION

This chapter addresses the entire South Florida Ecosystem, cutting across the artificial boundaries of the 10 subregions, as well as geopolitical and geomorphological boundaries, to present the broader issues of developing an interagency and interdisciplinary ecosystem-based science program to support South Florida Restoration. Here are presented the general premise and approach, with brief discussions on monitoring, modeling, and special restoration support studies. This chapter is not intended as a comprehensive synthesis or overview of subsequent chapters of this report. Rather, it deals with major cross-cutting issues, including management aspects of the science effort, and identifies critical gaps in coverage, which occur particularly at the boundaries between subregions and disciplines.

BACKGROUND

Water is life for South Florida's human and natural systems. Clean, abundant water was a fundamental characteristic of the original South Florida Ecosystem. The increased human population and human activity in South Florida have brought not only an increased need for water but also deterioration in water quality and a decrease in water supply. The latter was caused by loss of dynamic, or short-term, water storage capacity that accompanied drainage. Alterations in the hydrologic system are thought by many to be the root cause of dramatic declines in fish and wildlife populations and their habitat across the South Florida Ecosystem.

The basic premise of the restoration effort is that better water management will provide sustainability across both human and natural systems. Therefore, the working hypothesis of the adaptive management approach adopted by the Interagency Working Group is that hydrologic restoration is the prerequisite to ecosystem restoration. This is consistent with conclusions of a panel of independent scientists that hydrologic restoration may be the best option for achieving recovery of wetland-dependent endangered species (Orians et al. 1992). To resolve the hydrologic issues is the first concern. The highest priority science is that which determines how to modify the structure and operation of the hydrologic system to accomplish restoration. Some systems (e.g., uplands) may, however, require focus on additional restorative approaches.

The predrainage, or natural, hydrologic system supported the landscape patterns; clean and abundant water supplies; and large populations of wading birds, game fish, and other wildlife characteristic of the predrainage ecosystem. Therefore, the natural hydrologic system, as reconstructed with hydrologic models, can provide general guidelines on how to design an ecologically supportive hydrologic system for South Florida. The conversion of natural lands to urban and agricultural lands that has already taken place in South Florida precludes exact reinstatement of the natural hydrologic system everywhere. It is expected that reconstruction of key features of the natural hydrologic system on public lands, or as they influence public lands and waters, will result in changes in the ecosystem in the right direction -- toward a sustainable healthy state.

MAJOR ISSUES

Note: Progress on several issues critical to South Florida restoration was stimulated by circulation of the draft of this report. Because of their importance, statement of all issues is retained in this final edition.

- Monitoring projects underway or planned by various agencies have not yet been coordinated or integrated into the South Florida Ecosystem Restoration effort. Major gaps in monitoring needs, considered regionally and in view of proposed ecological assessment indicators, are expected to be revealed by planned coordination and integration efforts.

► Past piecemeal attempts to solve environmental problems associated with the C&SF Project have led to the present seriously deteriorating state of the ecosystem. A holistic, region-wide ecosystem approach to monitoring, support studies, and modeling in a coordinated interagency and intergovernmental framework is the only means to attain restoration, but its achievement requires special effort and application of personnel and supporting resources.

► Hydrologic models currently existing or under development do not have the geographic coverage required to meet region-wide ecosystem management needs or to provide the hydrologic information for regional ecological models that are under development. With existing hydrologic models, the ecologic model cannot show whether a proposed water management strategy might increase feeding opportunities for wading birds in one part of the region without decreasing them to a greater extent somewhere else -- and then determine the consequences of these changes for resident wading bird populations. With existing hydrologic models, one cannot readily see what happens to water levels in Lake Okeechobee when the system is operated to restore near predrainage flows to Florida Bay.

► Existing hydrologic models do not extend to the coast and therefore cannot show how physical and ecological processes in the mangrove zone are affected by water management strategies. Furthermore, because they stop short of the coast due to lack of critical topographic data, existing hydrologic models cannot provide adequately detailed and realistic freshwater inflow data needed by the hydrodynamic models Congressionally mandated for Florida Bay to show how bay salinity and circulation patterns respond to freshwater inflow variations. Missing and requiring a major directed effort are hydrologic models with tidal and salinity components for the entire coastline of South and Southwest Florida. These models are needed to support regional ecological models of wading birds and fish and to provide input to hydrodynamic models of coastal waters.

► Restoration management using the adaptive management approach will be heavily dependent upon simulations from models, particularly hydrologic models. Yet the most suitable current hydrologic models cannot be used to test alternatives for the interagency restoration effort on a timely basis.

► Systems of nested models are needed, in which finer resolution can be provided to address some questions and coarser resolutions can be provided to address others.

► Modeling and special studies are most effective when complementary, but modeling is not well integrated with present scientific studies, and funds for modeling usually do not include sufficient funds for special supporting studies, including verifications.

► Use of models as technical tools in the restoration effort requires buy-in by all involved or interested parties. An objective process is needed to evaluate existing models within the context they are being used and ensure necessary improvements are made, while at the same time protecting useful models against attacks on their credibility. The fact that useful, credible models are available should not preclude development of new models that can address problems of resolution, scope, and flexibility.

► Certain key species (e.g., apple snail) or communities (e.g., periphyton) that might be suitable ecological indicators because of their important roles in the ecosystem or sensitivity to anthropogenic changes are so poorly studied they cannot be used as indicators. Furthermore, lack of knowledge about the response of these species or communities to hydrologic and nutrient variables may seriously handicap the restoration effort.

► Flexible and sustained resources are essential to an effective, comprehensive restoration effort. The various involved agencies have unique and complex funding strategies. There is no specific South Florida Ecosystem Restoration funding source. Thus, some critical activities needed at early stages in the restoration process are being neglected for lack of directed resources.

► Critical linkages between subregions are not being adequately addressed by agencies. Florida Bay is perceived as being in a crisis state, demanding immediate attention, and alteration in freshwater flow is thought to be a major contributor to its decline. Yet models that cover the critical mangrove zone between the Everglades and the bay are not yet under development, the topographic data required for the models are not yet being collected, and salinity data of the required spatial and temporal resolution to relate freshwater inflows to salinity and circulation patterns are not yet being obtained.

- Issues of agency authority are at times a barrier to focusing efforts at problem sources. Control of harmful nonindigenous plant species is an arena where there are jurisdictional gaps. The many aggressive upland species invading publicly owned natural areas are not included in major management and science initiatives, which appear confined primarily to control of aquatic weeds, melaleuca (*Melaleuca quinquenervia*), and agricultural pests. Soil subsidence is another arena where there may be jurisdictional gaps.

- Information exchange is a problem, because there is so much information in the hands of myriad sources, including local governments.

- Many people who live in South Florida do not realize the benefits they receive continuously from a functioning natural ecosystem and what ecosystem collapse would mean to them. Both tangible and intangible connections between natural and human systems need to be quantified and widely communicated while reinstatement of a sustainable system is still possible. Some obvious examples are decline of Florida Bay fisheries, elevated mercury concentrations in fish and alligators in the Everglades, and drinking water quality problems in South Florida water treatment plants.

- Potential opportunities need to be explored for configurations of land and water that lead to ecosystem restoration and enhanced quality of life and economic sustainability in human communities.

- Decision makers and the general public appear not to understand the consequences of development in wetlands. A scientifically based analysis is needed to demonstrate alternative futures under various land and water configurations.

- Agricultural applications of pesticides are enormous in South Florida, compared to other parts of the Nation, and the highly permeable nature of the South Florida substrate provides less protection against leakage into aquifers and aquatic environments than anywhere else in the U.S., yet there is no coordinated science program to support reduction in agricultural or urban pesticide usage.

- While monitoring for contaminants is extensive, little interpretation of monitoring results is occurring. Bioindicators are lacking for subtropical species and conditions (i.e., temperatures, high salinity, seasonal hypoxia, and concentration due to seasonal low rainfall coupled with high evaporation).

- An extensive program is developing to examine the effect of phosphorus loading on ecological balance in higher plant and algal communities; however, plant growth is affected by soil burdens of nutrients as well as nutrient concentrations in the water column. Dosing studies need to be augmented by gradient studies and process-oriented studies of nutrient cycling through soils, plants, algae, and the water column on different types of soils and under different types of hydrologic conditions.

OBJECTIVES

The goal of the Science Subgroup is to develop an interagency, interdisciplinary science program that will guide restoration actions by determining relationships between ecosystem function and hydrologic regime and describing hydrologic conditions required to support the characteristic landscapes, biodiversity, and wildlife abundance of predrainage South Florida. The major science objectives to accomplish this goal are shown in Figure 2. The science program will provide: 1) a scientific basis for management decisions (e.g., regulatory actions, land-use permitting), and 2) information that might lead to increased beneficial interactions between natural and human communities.

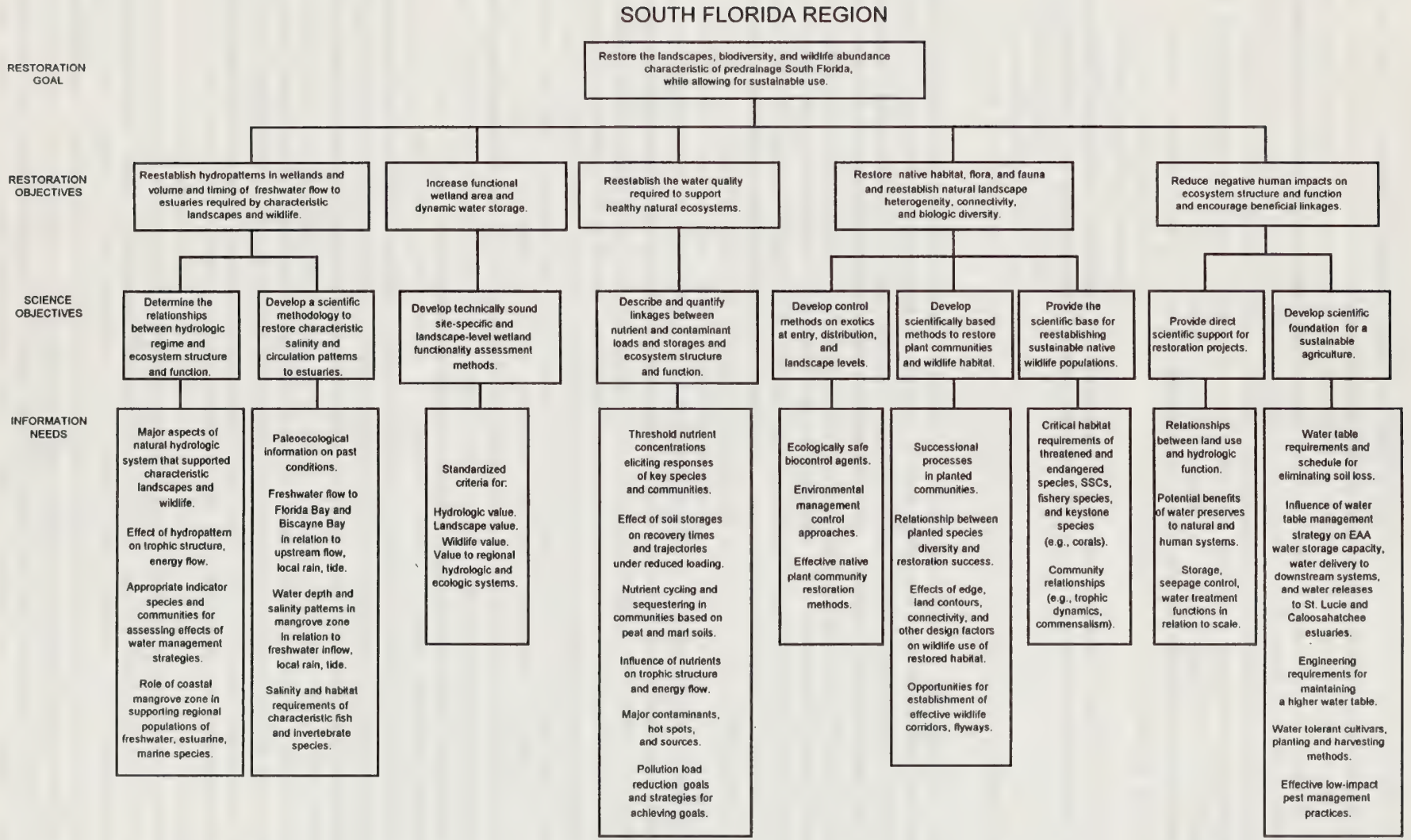

SOUTH FLORIDA REGION
RESTORATION GOAL
Restore the landscapes, biodiversity, and wildlife abundance characteristic of predrainage South Florida, while allowing for sustainable use.
RESTORATION OBJECTIVES
Reestablish hydropatterns in wetlands and volume and timing of freshwater flow to estuaries required by characteristic landscapes and wildlife.
Increase functional wetland area and dynamic water storage.
Reestablish the water quality required to support healthy natural ecosystems.
Restore native habitat, flora, and fauna and reestablish natural landscape heterogeneity, connectivity, and biologic diversity.
Reduce negative human impacts on ecosystem structure and function and encourage beneficial linkages.
SCIENCE OBJECTIVES
Determine the relationships between hydrologic regime and ecosystem structure and function.
Develop a scientific methodology to restore characteristic salinity and circulation patterns to estuaries.
Develop technically sound site-specific and landscape-level wetland functionality assessment methods.
Describe and quantify linkages between nutrient and contaminant loads and storages and ecosystem structure and function.
Develop control methods on exotics at entry, distribution, and landscape levels.
Develop scientifically based methods to restore plant communities and wildlife habitat.
Provide the scientific base for reestablishing sustainable native wildlife populations.
Provide direct scientific support for restoration projects.
Develop scientific foundation for a sustainable agriculture.
INFORMATION NEEDS
Major aspects of natural hydrologic system that supported characteristic landscapes and wildlife.
Effect of hydropattern on trophic structure, energy flow.
Appropriate indicator species and communities for assessing effects of water management strategies.
Role of coastal mangrove zone in supporting regional populations of freshwater, estuarine, marine species.
Paleoecological information on past conditions.
Freshwater flow to Florida Bay and Biscayne Bay in relation to upstream flow, local rain, tide.
Water depth and salinity patterns in mangrove zone in relation to freshwater inflow, local rain, tide.
Salinity and habitat requirements of characteristic fish and invertebrate species.
Standardized criteria for:
Hydrologic value.
Landscape value.
Wildlife value.
Value to regional hydrologic and ecologic systems.
Threshold nutrient concentrations eliciting responses of key species and communities.
Effect of soil storages on recovery times and trajectories under reduced loading.
Nutrient cycling and sequestering in communities based on peat and marl soils.
Influence of nutrients on trophic structure and energy flow.
Major contaminants, hot spots, and sources.
Pollution load reduction goals and strategies for achieving goals.
Ecologically safe biocontrol agents.
Environmental management control approaches.
Effective native plant community restoration methods.
Successional processes in planted communities.
Relationship between planted species diversity and restoration success.
Effects of edge, land contours, connectivity, and other design factors on wildlife use of restored habitat.
Opportunities for establishment of effective wildlife corridors, flyways.
Critical habitat requirements of threatened and endangered species, SSCs, fishery species, and keystone species (e.g., corals).
Community relationships (e.g., trophic dynamics, commensalism).
Relationships between land use and hydrologic function.
Potential benefits of water preserves to natural and human systems.
Storage, seepage control, water treatment functions in relation to scale.
Water table requirements and schedule for eliminating soil loss.
Influence of water table management strategy on EAA water storage capacity, water delivery to downstream systems, and water releases to St. Lucie and Caloosahatchee estuaries.
Engineering requirements for maintaining a higher water table.
Water tolerant cultivars, planting and harvesting methods.
Effective low-impact pest management practices.

Figure 2. South Florida region-wide goal, objectives, and information needs.

APPROACH

The scientific investigations identified in this report are directed at:

1. Characterizing the predrainage system and comparing it to the present system, particularly hydrologically.
2. Determining the key characteristics of the former natural hydrologic system that supported the rich diversity and abundance of wildlife that have been lost.
3. Designing structural and operational modifications of the C&SF Project that would recreate the key characteristics of the natural hydrologic system.
4. Assessing the hydrologic and ecological results of these modifications.
5. Modifying the design to make improvements.

Given this approach, adaptive management techniques are particularly appropriate. Following is a description of the adaptive management approach, as recommended for the South Florida Ecosystem Restoration effort.

Adaptive Management

Adaptive management is a structured, iterative approach for improving resource management. It accepts, *a priori*, the fact that information used in making resource management decisions is imperfect and, as decisions are implemented, a structure must be in place to gain better information and adjust the implemented action accordingly. This structure has three elements -- models, restoration support studies, and monitoring -- used as coordinated, supportive tools. Models (hydrologic, ecologic, etc.) provide a framework for restoration support studies that lead to development of better information. This information is used to propose alternative actions, which are then compared by means of models that simulate their consequences. Once an alternative is implemented, monitoring is used to test responses. Models help interpret monitoring data, and this information can be used to design better alternatives, as well as better models. All three elements are critical to successful restoration.

Periodic environmental assessment, utilizing modeling to predict outcomes and monitoring to test the predictions, is the operational foundation of the adaptive management approach. Adaptive management is a means of using the measured outcome of management actions to make corrections and adjustments in management actions that will improve the probability of achieving objectives. Preliminary modeling and follow-up monitoring are essential to the application of adaptive management, as is continuing substantive communication between scientists and managers.

Scale and resolution are major concerns in planning the related use of several models, and special attention should be given to addressing issues of scale and resolution early in the planning of restoration science. Scale and resolution in monitoring should be coordinated with model scales and resolution.

As applied in the South Florida Ecosystem Restoration effort, adaptive management does not necessarily mean large-scale experimentation but rather having a protocol in place to select among alternative actions and to gain useful information regarding ecosystem response to a restoration action, once it is taken. Implicit in selection of a management action is the hypothesis that the system will respond favorably to that action. Models help formulate this hypothesis. Monitoring is the means of testing the hypothesis. Models and monitoring are applied within the framework of an assessment protocol that identifies ecological indicators to be used in determining effects, defines how models will be applied at various stages of decision making, ensures models are designed to provide the output required for making evaluations, and focuses monitoring efforts.

Selection and use of appropriate ecological indicators is essential to success of the restoration effort. The indicators must be readily measurable and sensitive to the types of changes to be made. They should relate to restoring the characteristics of the natural system. Species and communities that play major roles in ecosystem function or reflect region-wide ecosystem function should be given priority. Several indicators should be selected, each with a different set of habitat requirements and representative of a larger group. Those species and communities for which information and time series of data already are available should be used initially as indicators.

The 1993 SSG report listed a number of restoration success criteria for evaluating progress of the restoration effort. Assessment indicators also have been presented by SFWMD (1993) and Hoffman (1994). Recently, the SSG revisited and updated its criteria as suggested restoration success indices. They were organized into two types: precursor success indices and ecological success indices. Precursor indices refer to conditions thought to be favorable to ecological restoration and are:

- Reinstatement throughout the system of natural hydropattern and sheetflow, as approximated by natural system models.
- Reduced body burdens of mercury in top carnivores.
- Reduced concentrations of known contaminants in canal surface sediments and the water column at SFWMD monitoring locations.
- Reduced rate of soil subsidence.
- Reduced phosphorus loading.
- Reinstatement of natural salinity patterns in estuaries.
- Reduced turbidity in estuaries.
- Increased ecotone/buffer area throughout the system.
- Increased spatial extent of wildlife corridors/greenways/flyways throughout the system.

Ecological indicators recommended by the SSG are:

- Reestablishment of predrainage wading bird nesting colony locations and timing of nesting.
- Improved recruitment of fishery and nonfishery species.
- Increases in fish abundances and reinstatement of species in pre-disturbance locations.
- Reduction in prevalence of deformed fish in estuaries.
- Increased diversity of native landscapes.
- Reappearance of missing vegetative landscapes.
- Reduction in expanses of nutrient-tolerant plant species.
- Reduction or elimination of invasive exotic plant species.
- Periphyton community taxonomic composition characteristic of oligotrophic, natural hydroperiod systems.
- Population increases in threatened and endangered species.
- Increased coral cover.

It would be a serious mistake to think restoration can succeed simply on the basis of modeling and monitoring. Field and laboratory studies that acquire critical information about the system must be a major part of development of scientific information to support restoration. Syntheses of available information, including historic information, in the context of present issues and questions is a necessary component of an effective science program.

Following are brief discussions of the monitoring, modeling, and support study needs of the restoration effort. Modeling is discussed in greater detail in a separate chapter. A chapter on mercury discusses modeling, monitoring, and support studies needed to address the mercury problem. Needs for restoration support studies and monitoring are covered in greater detail in chapters on nonindigenous species, protected species, and contaminants. Needs for restoration support studies and monitoring are the major focus of chapters on the 10 subregions.

Because planning of integrated scientific investigations is a dynamic process and more than a year has passed since the draft of this document was circulated, some information needs described in this report now are being addressed, indicating that the strategy of working together to synthesize needs, inventory planned activities, and communicate priorities and gaps is working. A strategic plan, updated annually, is needed to provide up-to-date information on critical needs and gaps. The precursor of such a plan, in addition to this Scientific Information Needs document, was a report produced for FY97 budget considerations (SSG 1995). It was used in financial planning for the integrated South Florida Ecosystem Restoration effort.

Monitoring

Long-term monitoring is essential to the adaptive management process. Only monitoring can systematically reveal the results of implemented management actions. Regular, systematic surveys of species, communities, and

conditions pertaining to certain ecological indicators will allow managers to evaluate the degree to which restoration is meeting its stated goals and objectives. Advance monitoring will help document baseline conditions, including seasonal and year-to-year variation. Comparison of monitoring results to expectations will provide necessary insight for fine-tuning assessment models.

Development of a comprehensive system-wide monitoring plan should be guided by an assessment protocol and should be oriented toward obtaining time series information on ecological indicators. The monitoring plan should coordinate the many ongoing and planned monitoring programs of governmental and nongovernmental entities throughout South Florida. Coordination of these efforts can ensure consistency in terms of spatial and temporal resolution and parameters covered and will prevent gaps, particularly in relation to ecological indicators.

Geospatial data are particularly critical to the South Florida Ecosystem Restoration effort. An active, ongoing process to integrate geospatial information over the Region will help ensure availability of high quality geospatial data. As a first step at interagency integration and coordination, representatives from the SSG, FGDC, FDEP, and SFWMD have conducted several workshops to encourage coordination, sharing, and mutual archival of all geospatial information regarding the Kissimmee-Okeechobee-Everglades watershed (Haddad et al. 1995). The workshops are preliminary to establishing a joint Federal, State, and local geospatial data agreement that ensures formal quality assurance and quality control, metadata protocols, and electronic retrieval-archival capabilities for coordination and data sharing. The workshops have been useful in identifying gaps in geographic areas and types of information covered. They have highlighted opportunities for further coordination and resource sharing (e.g., NBS-GAP, NOAA C-CAP, FWS NWI, and FGFWFC Integrated Habitat Plan).

Modeling

Models are another critical component of the South Florida Ecosystem Restoration process. Modeling activities will involve design of new models or adaptation of existing models of the following types: models of physical processes (hydrologic, hydrodynamic, transport, and meteorological models); ecosystem models (landscape and ecological models); nutrient models; and models of the movements, chemical transformations, and bioaccumulation of contaminants such as mercury. These models must be integrated into an interactive modeling system.

Models are essential to the adaptive assessment process and must be used to help establish targets, select among alternatives, and interpret monitoring information to assess progress. Hydrologic models can reveal major characteristics of the South Florida hydrologic system prior to drainage and show how various proposed changes in water management may affect the hydrologic regime. Landscape and ecological models, linked to the output of hydrologic models, can help determine key features of the natural hydrologic system that were most important to sustaining a healthy ecosystem. Similarly, linked hydrologic, landscape, and ecological models can show -- given present population levels, organic soil deposits, sea level, and flood control and water supply requirements -- how characteristic natural landscapes and wildlife can most effectively be restored on public lands and in inland and coastal waters.

An integrated hydrologic modeling system covering the entire South Florida Ecosystem, developed from existing subregional models, is a major need. The output of hydrologic models is the required input to all other types of models. Hydrologic models can support model-based studies related to natural resource rehabilitation, as well as agricultural and urban sustainability. Fortunately, some hydrologic models that can be used in the restoration effort already exist, although replacements that can be more readily altered to simulate alternative management strategies are urgently needed.

The two most useful models to date are the South Florida Water Management Model (SFWMM) and its corollary, the Natural System Model (NSM). The SFWMM was developed by the District. The NSM, initially developed by the SFWMD and ENP, continues to be refined and improved by the SFWMD in conjunction with the SFWMM. These models will be the core of the proposed hydrologic modeling system until a new regional model, also being developed by the SFWMD, becomes available.

The "natural system" model is an important concept in the restoration effort. Natural system hydrologic models are models that have been calibrated for present-day conditions and then stripped of all canals and other control structures to approximate the predrainage hydrologic system (Walters et al. 1992; Fennema et al. 1994). The output of natural system hydrologic models provides an objective view of flow volumes, water movement, and surface water patterns in response to rainfall in the predrainage hydrologic system. Results of exploratory work with natural system models have provided invaluable insight on ways in which the hydrologic regime has been changed by the existing network of water control structures. The NSM is being used to help establish targets for hydrologic restoration. Because elevation changes have occurred in the Everglades due to subsidence of organic soils, predrainage topography has been reconstituted for the NSM to replace present topography and is being used in simulations beyond Fennema et al. (1994).

While hydrologic models are the first requirement of the restoration process, other models also are needed. Hydrodynamic models must be used to translate output of hydrologic models at the coastal edge into salinity, circulation, and mixing patterns in the estuaries. Special hydrologic-hydrodynamic models are needed to approximate water depth and salinity patterns in the mangrove zone, which is influenced by freshwater inflow, seasonal and long-term sea-level changes, and tide. Ecologic models are needed to translate hydropatterns in freshwater and mangrove areas into ecologically meaningful outputs (e.g., wading bird reproductive success) and to relate salinity and circulation patterns to secondary productivity and ecosystem health in the mangrove zone and estuaries.

Meteorologic models are needed to simulate rainfall and wind on dense spatial grids in areas where it is sparsely measured, such as the mangrove zone and Florida Bay. Meteorologic models can be linked to hydrologic models to help determine the effect that present and future water management strategies may have on rainfall patterns. Water quality models are needed to measure the effect of water management strategies on water quality in both freshwater wetlands and estuaries.

Model development currently underway at the SFWMD is vital to the restoration effort. In addition to hydrologic models, the SFWMD also is developing the Everglades Landscape Model that will be very useful. This model has the capability to allow vegetation changes, brought on by hydrologic changes, to further change the hydrologic regime. It also has the ability to follow soil accumulation and subsidence processes, as affected by hydrologic regime. The SFWMD is engaged in other modeling, monitoring, and process-oriented studies focused primarily on resolution of water quality problems, especially phosphorus. We propose integration of SFWMD activities with Federal efforts into a comprehensive South Florida Ecosystem Restoration Science Plan.

Empirical Restoration Support Studies

Empirical studies are the third essential element of the adaptive management approach. Science projects that should be given the highest priority in planning are those that address critical issue-related questions about the system, assist in designing hydrologic modifications to the system, and/or increase the reliability of the ecological assessment procedure. Species, communities, and approaches for empirical studies are discussed in the context of special topics or subregions in subsequent chapters.

Selection and use of appropriate ecological indicators is vital to the restoration effort. There is, therefore, a compelling need to learn more about native wildlife populations and vegetation communities, particularly their responses to hydrologic conditions, nutrient loading, catastrophic events, climate changes, and accumulation of contaminants such as mercury. Species and communities that play especially important roles in ecosystem function are appropriate subjects for ecological assessment indicators, especially if known to be sensitive to hydrologic alteration. Species should be selected that will represent groups of species with different habitat requirements. For instance, the wood stork and the snail kite would be complementary. Both are sensitive to hydrologic regime, but each has different requirements. The American alligator, which has another set of requirements, might be another complementary addition to this selected group. Indicators of region-wide ecosystem function would be particularly useful. The wood stork and other wading bird species, because their feeding ranges are large, integrate information on secondary productivity and hydropatterns across broad areas in their choice of colony sites and production of fledglings. Pink shrimp, because they are a major prey of many fish species, represent the overall productivity of the estuarine ecosystem with their recruitment to the Tortugas fishery.

Initially, ecological assessment measures should be based on those species and communities to which considerable scientific attention has been given in the past so that both time series of data and an intellectual basis for model design are available. Other key species or communities should be identified for new scientific investigations that will provide a basis for using them to measure restoration success. Apple snails, crayfish, prawns, and some of the aquatic herpetofauna are examples of ecologically important species about which little is known concerning their population biology and ecology. Forage fish and macroinvertebrates in both freshwater and coastal wetlands are seriously understudied, yet important in the transfer of energy through food webs. The apple snail, for instance, is the sole food of the endangered snail kite and also is an important food source for many other Everglades animals. The periphyton community makes up as much as half the biomass in parts of the Everglades and is thought to be an important food-web base. Although some information is available with which to develop an ecological indicator based on periphyton, this community is poorly studied, considering its complexity, its relative biomass, and the importance of microscopic algae as an energy and nutrient source for many aquatic organisms.

Studies should be conducted on species of special concern, particularly those listed as threatened or endangered under the Federal Endangered Species Act or by the State of Florida. The large number of endangered and threatened species in South Florida reflects loss of habitat and alteration of ecological processes. Better information about these species will make recovery of these populations as part of ecosystem restoration more likely. Science topics directed toward recovery of species are given in Table 1. Information needs for some protected species and species of special concern are presented in Table 2.

Field studies and field experiments, such as nutrient dosing studies and small-scale tests of the effect of altered hydropatterns or waterflow patterns, are needed to help separate the influence of causal factors. Paleoecological studies that lead to a better understanding of past conditions, effects of major aperiodic events, and past and future effects of ongoing processes such as sea-level rise also are critical to successful restoration.

Recurring but unpredictable events such as hurricanes, freezes, and fires will influence the success of ecosystem restoration, and their effects must be understood. Aftermaths of these events provide priceless opportunities to gain understanding of the system that would not otherwise be obtained, as studies following Hurricane Andrew are demonstrating.

Environmental conditions vary naturally in South Florida's wetlands due to seasonal rainfall and stochastic events such as hurricanes and fires. As human population pressures on wetland ecosystems increase, it is crucial to be able to distinguish effects of natural variation on aquatic communities from the effect of human interference. Surprisingly little is known about community structure and energy-flow pathways of South Florida's aquatic systems and their responses to changes in environmental conditions. Trophic pathways leading to secondary production that supports wading birds, alligators, and other major predators of this system are particularly poorly known. Exotic species are becoming significant components of these communities in some areas. Their roles in these communities and effects on native species are unknown.

Field and laboratory studies that are integrated with modeling efforts will enhance the information obtained from both approaches to scientific investigation. Models become more effective over time as relevant information concerning input and design modification is acquired. A list of special studies particularly needed in critical modeling work is given in Table 3. Several special studies are already taking place in conjunction with related modeling. The value of their results will be magnified by their use for designing, refining, or quantifying models.

Considering the compelling need to better understand the natural system before it was impacted by modern development, relatively little paleoecological work has been done in South Florida. Records of pollens, algal tests, and mollusk shells in soil cores can reveal past landscape patterns and concurrent environmental conditions. Results of such work could help augment efforts to visualize South Florida hydrologic and ecological systems prior to modern development, provide a historic perspective within which to view current ecological problems, and show how landscapes and species responded in the past to catastrophic events and climate and sea-level changes. Initial emphasis of paleoecological work should be on the central Everglades, the mangrove zone, and northern Florida Bay.

Table 1. Proposed special studies.

Recover Populations of Rare, Threatened, and Endangered Species:

- Identify species "on the brink" of listed species status.
- Determine ecological requirements for species recovery, especially considering interaction with other native flora and fauna (using GIS-based, integrated, multispecies approach).
- Assess status and trends of all threatened and endangered species and ongoing interactions with other native flora and fauna (using GIS-based, integrated, multispecies approach).

Restore Native Community Structure in Terrestrial, Freshwater and Marine/Estuarine Ecosystems:

- Assess status and trends of community structure in key assemblages such as coral, seagrass, wading birds, fish, and hardwood hammocks.
- Identify and understand major influences (i.e., nutrients, mercury, pesticides, habitat alteration, hydrologic alterations, and global change) on natural community structure and productivity.
- Determine role of point and nonpoint inputs of nutrients, mercury and pesticides in regulating community structure, and primary and secondary production patterns and trends in freshwater ecosystems.
- Determine role of natural and modified hydrology in regulating primary and secondary production patterns and trends.
- Assess effect of freshwater and nutrient inputs on community structure and productivity of marine and estuarine ecosystems.

Halt and Reverse Invasion of the South Florida Ecosystem by Exotic Fauna and Flora:

- Identify potential pathways for new introductions.
- Determine factors that influence susceptibility of faunal and flora communities to exotic invasion.
- Develop environmentally "safe" biologic controls for exotics.
- Identify non-native species that have potential to become problematic, especially due to restoration activities.
- Identify effects of invasive exotics on natural community and ecosystem biodiversity.

Table 2. Proposed studies on protected species and species of special concern.

	Population Dynamics	Habitat require-ments	Trophic relations	Census
Birds				
Cape Sable seaside sparrow	X	X		
Wood stork	X	X	X	X
Snail kite	X	X	X	X
Bald eagle	X			X
Red-cockaded woodpecker	X	X	X	X
Coot				X
Limpkin				X
Anhinga				X
Mammals				
Florida panther		X	X	
Lower Keys marsh rabbit				X
West Indian manatee		X	X	X
Round-tailed muskrat				X
River otter				X
Reptiles				
Sea turtles		X		X
American crocodile	X			X
American alligator	X	X		X

Table 3. Studies that will help develop an information base for assessment indicators and models.

Wading Bird Studies

- Systematic Reconnaissance Flights
- Nest success studies
- Foraging habitats
- Colony census
- Parasite studies

Freshwater Fish Studies

- Expand current sampling
- Life history parameters (otolith)
- Food-web studies (gut content, isotope studies)
- Bioaccumulation (mercury)
- Genetics study
- Predator-prey studies (mesocosms)

Freshwater Invertebrate Studies

- Community composition
- Food webs (gut content, isotope studies)
- Biocontaminants
- Predator-prey studies (mesocosms)
- Autecology of key prey species of higher organisms, particularly apple snails,crayfish, and prawns
- Microinvertebrate communities associated with periphyton

Herpetofauna Studies

- Autecology of major wetland species, particularly snakes and frogs.

Mammal Studies

- Range expansion of feral pigs
- Census of declining species

Nonindigenous Animal Species Studies

- Non-native survey
- Life history
- Control studies
  (a) Invertebrates
  (b) Fish

Substrate Profile Studies

- Peat mass, peat accretion rates (marker horizons throughout Everglades)
- Paleoecological studies

Support Landscape Model Development

- Landscape/vegetation
- Gradient analysis
- Soil surveys
- Topographic surveys
- Succession models (macrophyte/periphyton)

Support Integration with Faunal Models

- Fish community-based
- Wading bird community, statistical habitat
- Snail kite (statistical habitat)
- Deer/panthers

Threshold Studies

- Mass balance models
- Internal cycling and transport models
- Carbon flux models-foodweb
- Phosphorus loading measures (monitoring)
- Pesticides (sources, transport, fate)

Monitoring

- SWIM and EFA required monitoring
- Restoration assessment monitoring (success measures)

Florida Bay Studies

- Photointerpretation to map bottom habitat
- Bottom topography
- Sedimentary record (disturbance frequency and change in deposits)
- GPS surveys (tide gauges)
- Salinity mapping under various conditions of freshwater inflow
- Hydrodynamic modeling
- Ecological studies relating marine resources to salinity and other environmental variables

Opportunities should be sought for medium-scale experiments to determine how landscapes and wildlife respond to manipulation of water regime and nutrient loads. The Frog Pond, Hole-in-the-Donut, Holey Land, and Rotenberger Tract are possible experimental sites in which hypotheses on how to restore characteristic natural landscapes could be tested. Every implemented modification of the C&SF Project that is expected to improve ecological conditions should be treated as an experiment that tests the hypothesis that ecological conditions will improve in certain ways.

The existing literature, including early studies, should be reexamined for clues about the predrainage system, the influence of catastrophic events, geologic processes, and the relationship of landscape patterns to functionality. The restoration effort provides today's scientists with new perspective for reviewing and synthesizing previous work.

Evolving Mutually Supportive Human and Natural Ecosystems

To accomplish the goals of the South Florida Restoration effort, it is necessary to: 1) recreate for South Florida's remaining natural areas the overall hydrologic support functions that, prior to drainage, were provided by lands now occupied by urban and agricultural development; and 2) improve quality of life for human populations.

Issues of land use, routing of stormwater runoff, and disposition of treated wastewater all relate to concerns for human water supply as well as protection of natural areas. Loads of nutrients, various contaminants, and total organic carbons associated with human alterations of the system relate to water quality. Several scientific investigations recommended in this report address these problems. Water quality is affected by land use and practices of individuals and industries. Finding a harmonious balance between South Florida's human populations and the natural ecosystem requires resolution of major issues concerning release of nutrients and contaminants into surface and ground waters. These issues and relevant scientific information needs are discussed in several subregion chapters.

The Everglades Settlement Agreement, Everglades Forever Act, and Clean Water Act mandate that threshold concentrations be determined for effects of phosphorus on the ecological balance of native flora and fauna. Dosing studies can show the concentrations of phosphorus that invoke changes in wetland communities. Other studies can show how best to reduce input of nutrients at the source and by passage through wetland water treatment areas. In addition to dosing studies and field studies already underway in the EAA and STAs, process-oriented and gradient analysis studies need to be conducted to determine how nutrient burdens in soils affect plant community composition and how best to restore native vegetation natural to a site.

Contaminants are another serious water quality concern in South Florida. Mercury has gained notice because of the human health hazard associated with its observed bioaccumulation in fish and higher organisms. Other contaminants also pose serious problems in South Florida. Biscayne Bay was in the top 10 of a ranking of estuarine drainage areas based on the potential of inventoried pesticides to impact estuarine organisms (Pait et al. 1992). The 1991-1992 Green Index (Hall and Kerr 1991) ranked Florida the worst state according to a composite water pollution index.

Pesticides and polycyclic aromatic hydrocarbons are present in the South Florida Ecosystem. Some pesticides (e.g., endosulfan) and PAHs (4- and 5-ring aromatics) are acutely and chronically toxic compounds. Because many are estrogen hormone mimics, possible chronic effects of these compounds include disruption of reproduction in wildlife and aquatic organisms. Endosulfan has a high bioconcentration potential and it or its breakdown products may accumulate in food chains. Furthermore, it has estrogenic properties that could potentially cause alteration of sexual development in both wildlife and humans. Atrazine, an herbicide heavily utilized in South Florida to control agricultural weeds, is another compound with estrogenic effects. Nemacur (active ingredient fenamiphos), widely applied to golf courses, causes fish kills when flushed to nearby waters after heavy rains, and leaching of Nemacur to groundwaters is also a serious concern (Zaneski 1994). Organic contaminants are the topic of a separate chapter in this report.

Water quality can be affected by water management. Trihalomethanes, which have been associated with human cancer and genetic defects, form in water treatment plants by an interaction of chlorine with dissolved organic matter found in raw water supplies. Water management affects the DOC in the raw water. The Biscayne Aquifer, which supplies most of the drinking water for Southeast Florida, is recharged not only by rainfall but also by canal flow from Lake Okeechobee and the Everglades. Natural Everglades waters were very clear, indicating a low content of DOC; however the DOC level is very high in South Florida canals. DOC is released into South Florida's waters by oxidation of drained organic soils and proliferation of algae and aquatic weeds in canals. Although technological methods are used by South Florida water treatment plants in order to reduce contamination of drinking water with chlorine byproducts, these solutions all have their problems and the best solution is very expensive. A water management approach to reducing trihalomethane formation should be explored in association with the South Florida Restoration effort.

Land use affects water supply as well as water quality. South Florida's water shortage problems are not so much an allocation problem as a problem of where to store the abundant wet season rainfall so it can be used during the dry season. Land-use decisions ultimately affect the amount of water that will be stored on land and in surficial aquifers. As more and more land is developed, it becomes more important for decision makers to recognize the influence of land use on water supplies and the ability to manage water both to restore natural systems and to serve urban and agricultural systems. Several proposed scientific investigations for the Lower East Coast Urban Area deal with quantifying and demonstrating the relationships between land use and water management.

Wetland regulatory programs and planning programs require technically sound methods for evaluating wetland functionality. This information is required for informed permitting decisions that take into consideration functions that a particular wetland area provides, including its role and contribution to the greater ecosystem. Wetland assessment approaches must be developed at two scales: landscape and site-specific.

South Florida has productive agricultural systems that could contribute to -- and benefit from -- ecosystem restoration. The EAA now contains a productive agriculture of major economic importance to the Region. However, this agriculture is on organic soils that are losing depth, primarily due to microbial oxidation resulting from drainage. The continued loss of soil is a severe agricultural concern that limits the lifetime of agriculture in the area. Release of phosphorus and dissolved organic carbons into drainage waters are environmental concerns associated with soil subsidence. Previous studies suggest that a zero-subsidence agriculture producing present crops and maintaining current harvest levels may be possible. A science program is proposed with the objective of developing the technology for this zero-subsidence system. It is possible that successful investigations would help modify the hydrologic function of the EAA, with respect to downstream natural ecosystems, to more closely resemble its predrainage function (i.e., providing dynamic storage and allowing conveyance of water from Lake Okeechobee). Management of water for zero subsidence and for improved quantity, timing, and location of flow to downstream natural systems might be compatible if control of subsidence can be accomplished by delaying release of wet season rainfall. A science program to halt subsidence while maintaining a profitable agriculture is described in the Subregion 4 chapter.

Many Federal, State, and local agencies operate in South Florida and, through regulation, taxation, insurance, subsidies, or other means, influence the course of events in not only deliberate but also inadvertent ways. Coordination of government efforts should involve identifying pertinent agency programs and policies and evaluating their influences. This should lead to recommendations that would improve consistency of government programs with the overall effort to restore the South Florida Ecosystem.

INFORMATION NEEDS

Critical scientific information needs identified for the South Florida Ecosystem as a whole are shown in Figure 2 in relation to the overall restoration goal and to specific scientific and restoration objectives. These needs are detailed in other chapters in this document on individual subregions or special topics. The following set of recommendations focuses on the process of scientific information development to fulfill the information needs in Figure 2 and highlights a few critical information gaps.

- **Develop an assessment protocol that helps focus modeling and monitoring activities on predicting and measuring restoration success indicators. Identify core modeling and monitoring needs. (Lead--SSG)**

An assessment protocol is needed to help focus monitoring efforts and define how models will be applied at various stages of the restoration effort. The assessment protocol must be developed concurrently with model development and preparation of a monitoring plan. Modelers and those involved in developing the monitoring plan should take part in preparing this protocol.

- **Establish a set of ecological indicators, starting with the assessment criteria recommended by SSG (1993). (Lead--SSG)**

Refine the original list of assessment criteria into a set of practical and sensitive indicators and develop them into an effective assessment tool. Coordinate selection of indicators with ongoing modeling and monitoring activities.

- **Propose potential ecological indicators for which little information is available and target these species or communities for special scientific investigations.**

Several key species and communities in the environment would be appropriate ecological indicators, except that little is known about them. For instance, the apple snail is the critical prey of several species, including the endangered snail kite, yet little is known about its population biology and ecology.

- **Establish groups to model the hydrologic, hydrodynamic, landscape, meteorologic, and ecologic processes of the South Florida Restoration area and develop an integrated region-wide modeling system. (Lead--SSG)**

Upgrade existing grid-based hydrologic models (SFWMM and NSM) and develop new ones to cover areas presently lacking coverage, including, particularly, the mangrove zone. Design a new generation of hydrologic models that can be more easily used to test alternatives. Develop a hydrodynamic model for Florida Bay to predict circulation, mixing, and salinity patterns in Florida Bay as a function of freshwater inflow and other variable factors. Support the hydrodynamic model with a regional numerical ocean circulation modeling system that can provide boundary conditions for the Florida Bay model. Develop ecological models that will translate hydrologic information into effects on the ecosystem.

- **Initiate ecological model development at the beginning of the restoration effort and integrate it with development of hydrologic and hydrodynamic models.**

Ecological models, even with cursory data, can identify the type of information that must be obtained from hydrologic and hydrodynamic models and illustrate why this information is needed. By developing ecological models concurrently with the hydrologic and hydrodynamic models to support them, scientists can ensure hydrologic and hydrodynamic models will provide suitable support for addressing ecological questions.

- **Fund modeling projects sufficiently to allow these projects to finance related special studies involving field and/or laboratory work.**

The best results are achieved if modeling is initiated at the beginning of the project rather than delayed until more information is obtained, and if special studies to obtain the necessary information are funded through the modeling group.

- **Integrate modeling with monitoring and science planning and use models to help organize information, communicate concepts and ideas, design studies, and identify critical information needs.**

Initiate modeling at the beginning of scientific studies rather than at the end to help ensure the studies are complementary and gaps in information are minimized. Models should be an essential component of investigations

that include field studies, experiments, laboratory analyses, and other means of obtaining information. Models can be used to integrate results from several studies into a higher order of information.

▸ **Ensure the continued development and upgrading of natural system models as part of the hydrologic modeling effort in order to provide input data for ecological models.**

Comparison of the present system with the predrainage system is important to developing restoration targets. The best guide for understanding the ecological ramifications of changes in spatial extent and hydrologic conditions that have occurred is the simulated output of spatially explicit "natural system" hydrologic models supporting a system of ecological simulation models that operate at several scales.

▸ **Acquire critical freshwater inflow and salinity information required to develop and calibrate a hydrodynamic model for Florida Bay.**

A hydrodynamic model for Florida Bay will help determine the relationship between freshwater inflows and patterns of circulation and salinity. Freshwater inflow and salinity are major data requirements for hydrodynamic models. Current SFWMM and NSM models do not extend the full distance to Florida Bay and do not have the resolution and data to provide reliable flow estimates to Florida Bay. Spatial extension of these models or development of separate, connecting models of the mangrove zone (as suggested below) is a critical first step to understanding relationships between freshwater flow and bay salinity and circulation patterns. A high degree of resolution in salinity data is necessary to develop and calibrate hydrodynamic models. Augmentations and improvements in salinity monitoring programs are needed to support hydrodynamic modeling.

▸ **Acquire needed topographic data and develop models to simulate freshwater inflow, water depths, and salinity patterns within the mangrove zone and freshwater inflow to Florida Bay, Biscayne Bay, and the Gulf of Mexico.**

Physical models of the mangrove zone are a critical missing element in the overall restoration modeling effort. They are needed not only to connect existing water management models to estuaries, but also to simulate water depths and salinities in the mangrove zone so the effect of proposed water management strategies on ecological processes, such as reproductive success of wading birds, can be modeled.

▸ **Develop a monitoring plan, bringing together in workshop settings the major participants in present and proposed monitoring efforts. (Lead--SSG)**

Conduct special monitoring-related topic workshops, such as the Spatial Information Workshop of September 1994, to: 1) consider restoration assessment needs from monitoring, 2) explore current capabilities, 3) discuss existing monitoring activities and monitoring plans, 4) adopt common quality control procedures, 5) coordinate efforts, and 6) share resources and information. Prepare a comprehensive, integrated monitoring plan from results of these workshops.

▸ **Review and synthesize the historic and recent literature in the context of major issues and questions in the restoration effort.**

▸ **Develop the information base for application of the adaptive management approach, emphasizing determination of important relationships and building assessment capability. (Lead--SSG)**

Conduct special studies integrated with modeling and monitoring and acquire information that can be used in assessment to support the adaptive management strategy. Strengthen the scientific understanding that will enable effective management actions to be proposed and implemented (e.g., determine how vegetation communities and wildlife are affected by hydrologic regime, anthropogenic nutrients, and contaminants). Focus especially on species and communities that are proposed ecological indicators. Utilize the workshop approach, bringing together appropriate parties, including modeling and monitoring participants, as well as the management community.

▸ **Develop scientific information and tools to support a multispecies ecosystem approach to the protection of endangered and threatened species.**

Use GIS, remote sensing, food-web analyses, modeling, and other techniques to characterize critical habitat and environmental requirements for protected species.

▸ **Conduct mesocosm studies to establish response thresholds for phosphorus concentrations. Expand nutrient studies to include soils.**

Examine ecological balance in native flora and fauna in relation to phosphorus concentrations in inflowing waters and soils.

▸ **Identify critical gaps in the pathways toward development of the scientific information and tools needed for ecosystem restoration. (Lead--SSG)**

Sometimes progress in preparing information and tools is inadvertently delayed by lack of support for a critical link in the overall process. Such delays can be prevented by showing connections between projects required along important pathways.

▸ **Develop and apply methods to relate socioeconomic conditions and human actions to ecosystem health in South Florida.**

Human and natural ecosystems are mutually dependent, but these dependencies are not always recognized by decision makers. Science-based information specific to South Florida is needed to demonstrate the interdependency and point out opportunities to improve overall sustainability within the context of restoring the ecosystem.

▸ **Develop scientific studies that will lead to productive, supportive interactions between natural and human systems.**

In general, studies must address these questions: What are the critical feedbacks of the natural system to urban and agricultural systems and vice versa? How will the natural system and its support functions for humans be affected by different population levels and land-use configurations? What landscape combination will allow healthy natural systems and urban and agricultural systems to coexist?

▸ **Conduct "consistency" analyses to determine present or potential influences of government activities (e.g., laws, programs, policies) on efforts to restore the South Florida Ecosystem.**

Identify those programs and laws of government agencies that, through regulations, grants, tax incentives, or otherwise, may undermine the intergovernmental, science-based effort to restore the South Florida Ecosystem and those that can potentially enhance the ecosystem restoration effort. Give particular emphasis to factors that influence encroachment of urban or agricultural development into remaining wetlands and remaining upland natural areas.

▸ **Develop technically sound *landscape-level* wetland functionality assessment methods that can be used by wetland regulatory and planning programs to make appropriate decisions.**

The landscape-level wetland assessment method must be developed and implemented for all wetlands within the SFWMD boundary during development of the South Florida Comprehensive Wetlands Conservation, Mitigation, and Permitting Strategy. The methods should be capable of evaluating wetland areas into general high/medium/low functional categories. Landscape ecology concepts and GIS approaches should be employed. The methods should facilitate evaluating a particular wetland and its functionality in the context of the greater ecosystem and should be user friendly.

▸ **Develop *site-specific* wetland functional assessment methods that can be used by regulatory and planning programs as a basis for making appropriate decisions.**

Several different approaches currently are used for assessing development impacts and determining mitigation requirements, such as analyses based on ratios, relative scoring values, and integrated matrices. Consequently, there is no continuity of assessment techniques among projects, and it is difficult to compare results. The needed method should facilitate evaluating a particular wetland and its functionality in the context of the greater ecosystem, should be relatively easy and rapid to employ by professionals in the geographic area of application, and must produce consistent assessments of wetland impacts as well as uniform determinations of mitigation requirements. The method must also be realistic in terms of the volume of data required for specific wetland areas and take into consideration whether the assessment is done during the wet season or during the dry season.

▸ **Provide continuous support as an integral part of restoration operations budgets for this multiyear adaptive management effort. (Lead--SFERTF)**

Adaptive management for ecosystem restoration requires continual predictions and feedback from the interactive modeling, monitoring, and special study efforts -- and thus, continuous support.

▸ **Ensure resources to support planning, coordination, and oversight activities of the SSG. (Lead--SFERTF)**

A special annually replenished fund should be made available for SSG activities relating to planning, coordination, peer review, and other oversight activities needed to expand and strengthen the scientific basis for ecosystem restoration to ensure participation by all critical parties, Federal and non-Federal (including academic scientists).

BIBLIOGRAPHY

Fennema, R.J., C.J. Neidrauer, R.A. Johnson, W.A. Perkins, and T.K. MacVicar. 1994. A computer model to simulate natural South Florida hydrology. Pages 249-290 *in* S. M. Davis and J. C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Haddad, K., P. Matthews, T. Culliton, D. Lott, and J. Thomas. 1995. Interagency Spatial Information Workshop on the South Florida Ecosystem. Volume 1, Workshop Proceedings, and Volume 2, Information Surveys. West Palm Beach, Florida, September 22-23, 1994. FGDC, FDEP, NBS, NOAA, SFERTF, and SFWMD.

Hall, B. and M. L. Kerr. 1991. 1991-1992 Green Index. Island Press, Washington, D.C.

Hoffman, W., editor. 1994. Report of the Everglades Restoration Success Workshop. NAS, Tavernier, Florida.

Orians, G.H., M. Bean, R. Lande, K. Loftin, S. Pimm, R.E. Turner, and M. Weller. 1992. Report of the advisory panel on the Everglades and endangered species. Audubon Conservation Report No. 8. NAS, New York.

Pait, A.S., A.E. De Souza, and D.R.G. Farrow. 1992. Agricultural Pesticide Use in Coastal Areas: A National Summary. Strategic Environmental Assessments Division, National Ocean Service, NOAA, Rockville, Maryland.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Science Sub-Group. 1995. Science priorities and gaps: considerations for budget planning. Report of the Science Sub-Group, South Florida Ecosystem Restoration.

South Florida Water Management District, Planning Department Staff. 1993. Draft working document in support of the Lower East Coast Regional Water Supply Plan. SFWMD, West Palm Beach, Florida.

Walters, C., L. Gunderson, and C.S. Holling. 1992. Experimental policies for water management in the Everglades. Ecological Applications 2:189-202.

Zaneski, C.T. 1994. Wildlife pays ultimate price for Florida's green fairways. July 11, 1994. The Miami Herald, Miami, Florida.

THREATENED AND ENDANGERED SPECIES

INTRODUCTION

The large number of threatened and endangered species within the South Florida Ecosystem reflects the substantial direct loss of habitat and alteration of ecological processes in the system. Patterns and quality of water flow through wetlands have been altered, and water tables have been lowered under remaining upland habitat. A total of 35 plant and 34 animal species (excluding whales) in South Florida are listed as threatened or endangered under the Federal Endangered Species Act (Wood 1994). Additional animal species are listed as threatened, endangered, or species of special concern by the Florida Game and Fresh Water Fish Commission. Many additional plant species are listed as endangered or threatened by the Florida Department of Agriculture and Consumer Services. The Florida Natural Areas Inventory and Florida Committee on Rare and Endangered Plants and Animals consider all of the above species and additional rare species and habitats. Revised species accounts prepared by the FCREPA are now being published in a series of volumes, "Rare and Endangered Biota of Florida" (e.g., Humphrey 1992; Moler 1992).

The National Audubon Society convened an independent panel of scientists to consider the challenge of recovering endangered species in the Everglades within the framework of a regional restoration program (Orians et al. 1992). This panel concluded that with proper planning, and with improved endangered species monitoring protocols, it should be feasible to move forward with restoration while maintaining or improving the status of populations of endangered species. The panel concluded that for wetland-dependent endangered species, restoration may be the best option for achieving recovery of these species. The panel further articulated the need for a comprehensive multispecies recovery plan for the Everglades and reassessment of critical habitats for each species.

Endangered and threatened species of the South Florida Ecosystem can be classified into two broad groups. The first is those wetland-dependent species for which restoration of natural hydropatterns and water quality should improve habitat. The second includes terrestrial species which may or may not benefit from restoration of freshwater conditions. These include species found in the uplands of the Florida Keys, pinelands and hardwood hammocks throughout the Region, the Kissimmee Prairie, Lake Wales Ridge, and the coastal ridges. The status of these species is determined by the amount, fragmentation, and isolation of remaining habitat (Robertson and Frederick 1994). Recovery of these species will, in many cases, depend on some interplay between the effects of habitat fragmentation, fire management practices, and extent of exotic invasions.

In development of restoration plans for South Florida wetlands, it has been hypothesized that wetland-dependent species will benefit, or at least will not experience adverse effects, from properly executed restoration. Close monitoring will be required to ensure these wetland species do not become extinct or further stressed as the system shifts from its current altered state to a more restored condition. Sequencing of restoration efforts through some adaptive management process may be necessary to ensure protection of some of these species. This raises a question of possible adverse impacts that hydrological restoration may have on terrestrial-dependent endangered species. Is it possible that species such as the Florida panther may have less habitat available following restoration?

REGIONAL RECOMMENDATIONS

At least five key components need to be included in science plans for all listed species:

1. Conduct censuses of breeding and wintering populations of all species at regular intervals throughout the Everglades basin. Census protocols must be repeatable, statistically sound, and standardized across the Region. New census protocols must be developed for some species.

2. Develop ecological studies that address critical management questions for each of the species. These data will be essential to develop restoration plans in a manner that ensures improvement in the status of the species within the system.

3. Undertake a population viability analysis for each species to help identify bottlenecks in their life cycles that must be addressed during restoration planning. Spatially explicit population models can be useful tools to evaluate the risks associated with future land-use patterns and potential benefits or risks associated with restoration actions.

4. Evaluate the status of State-listed species and other species or populations not currently Federally listed, but which may be threatened with extirpation in the South Florida Ecosystem. Develop science priorities from this expanded list of species of regional concern.

5. Append to restoration plans a multispecies recovery plan, which identifies potential conflicts between species recovery plans and restoration plans and describes protocols for addressing these conflicts.

The FWS has initiated development of a multispecies recovery plan for South Florida. Initially, species experts will be assembled to update species accounts, which will include current population status, threats, and establishment of specific criteria to define recovery goals. The focus will then shift to ecosystems (vegetative cover types) in South Florida, and experts will attempt to resolve potentially conflicting biological or ecological needs of individual threatened or endangered species. Finally, a methodology will be developed to assess the effects of proposed components of South Florida Ecosystem restoration and determine alternatives that will optimize net benefits to a variety of species, while ensuring no individual species will be jeopardized.

MAJOR ISSUES AND INFORMATION NEEDS

The scientific information needs for major taxonomic groups are addressed below, generally in sections on background, issues, current studies, information needs, and references for each group. The numbers of listed species given for each group are from Wood (1994) plus updated information from FWS. In addition to the groups discussed below, the Federal list includes two South Florida invertebrate species: Schaus' swallowtail butterfly (endangered) and Stock Island tree snail (threatened). Figure 3 summarizes the goal, objectives, and information needs for threatened and endangered species.

Plants

Background

The number of Florida plants thought to need special conservation measures has grown rapidly in recent years. As of June 1994, 554 taxa, roughly 15% of the State's native flora, were listed as endangered or threatened, or as official candidates for such status, by the State of Florida or the FWS. This figure is more than three times the number of species treated by Ward (1978) in the "Plants" volume of "Rare and Endangered Biota of Florida." It appears that approximately 55% of the combined State- and Federal-listed plant species occur or once occurred within areas that may be affected, at least marginally, by Everglades restoration. This estimate includes the listed plants found only in the Florida Keys.

The Federal list includes 30 endangered and 5 threatened South Florida plants. Of these, 23 (19 endangered, 4 threatened) occur in scrub habitat on the Lake Wales Ridge. The multispecies recovery plan will address protection and management of scrub to secure recovery of these species, along with the animals that inhabit the area, such as the Florida scrub jay, blue-tailed mole skink, sand skink, and Eastern indigo snake.

Five plant species endemic to South Florida pine rockland habitat are on the Federal list. These are: the endangered crenulate lead plant (*Amorpha crenulata*), Small's milkpea (*Galactia smallii*), tiny polygala (*Polygala smallii*), deltoid spurge (*Chamaesyce deltoidea*), and the threatened Garber's spurge (*Chamaesyce garberi*).

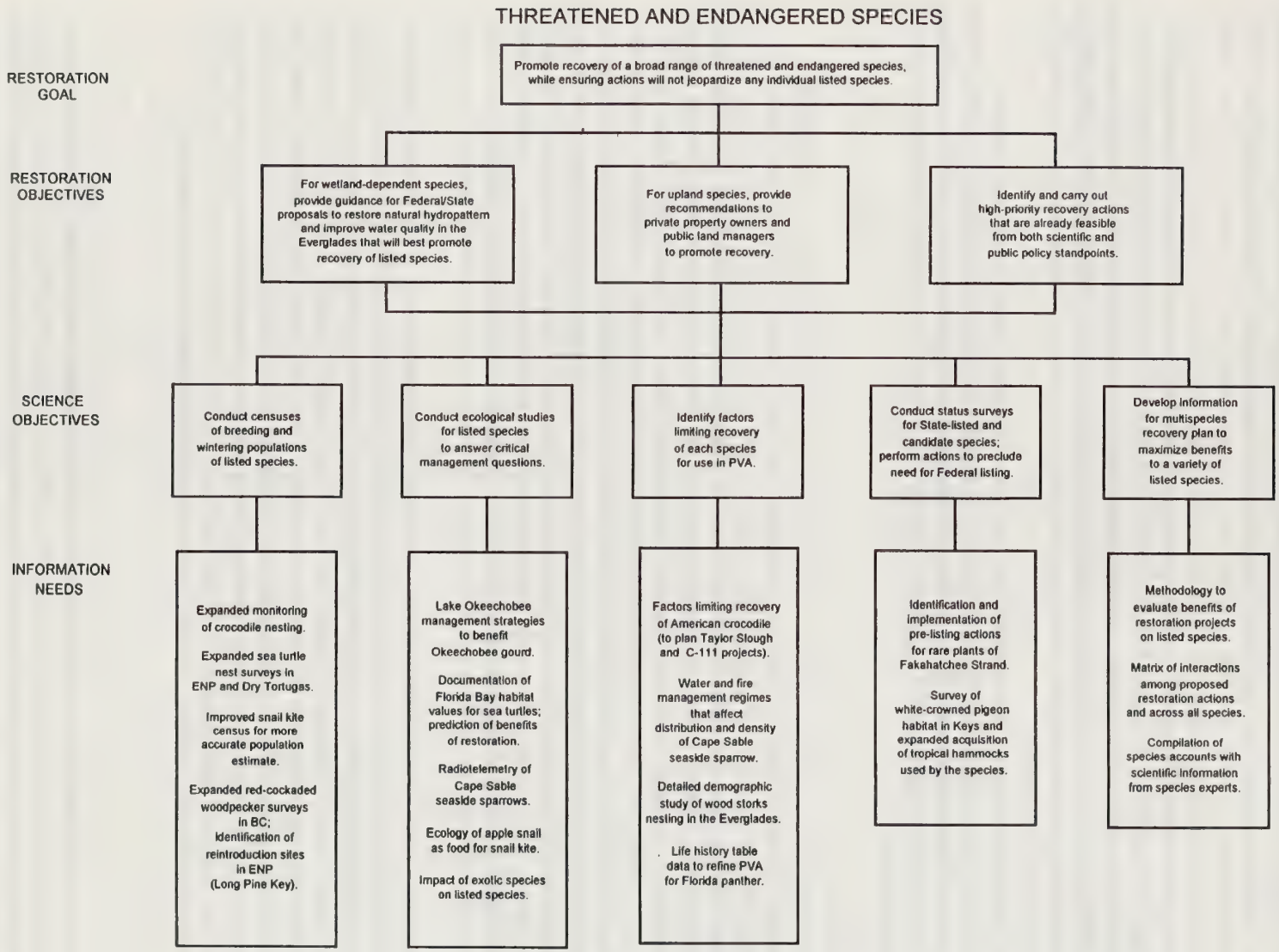

THREATENED AND ENDANGERED SPECIES
RESTORATION GOAL
Promote recovery of a broad range of threatened and endangered species, while ensuring actions will not jeopardize any individual listed species.
RESTORATION OBJECTIVES
For wetland-dependent species, provide guidance for Federal/State proposals to restore natural hydropattern and improve water quality in the Everglades that will best promote recovery of listed species.
For upland species, provide recommendations to private property owners and public land managers to promote recovery.
Identify and carry out high-priority recovery actions that are already feasible from both scientific and public policy standpoints.
SCIENCE OBJECTIVES
Conduct censuses of breeding and wintering populations of listed species.
Conduct ecological studies for listed species to answer critical management questions.
Identify factors limiting recovery of each species for use in PVA.
Conduct status surveys for State-listed and candidate species; perform actions to preclude need for Federal listing.
Develop information for multispecies recovery plan to maximize benefits to a variety of listed species.
INFORMATION NEEDS
Expanded monitoring of crocodile nesting.
Expanded sea turtle nest surveys in ENP and Dry Tortugas.
Improved snail kite census for more accurate population estimate.
Expanded red-cockaded woodpecker surveys in BC; identification of reintroduction sites in ENP (Long Pine Key).
Lake Okeechobee management strategies to benefit Okeechobee gourd.
Documentation of Florida Bay habitat values for sea turtles; prediction of benefits of restoration.
Radiotelemetry of Cape Sable seaside sparrows.
Ecology of apple snail as food for snail kite.
Impact of exotic species on listed species.
Factors limiting recovery of American crocodile (to plan Taylor Slough and C-111 projects).
Water and fire management regimes that affect distribution and density of Cape Sable seaside sparrow.
Detailed demographic study of wood storks nesting in the Everglades.
Life history table data to refine PVA for Florida panther.
Identification and implementation of pre-listing actions for rare plants of Fakahatchee Strand.
Survey of white-crowned pigeon habitat in Keys and expanded acquisition of tropical hammocks used by the species.
Methodology to evaluate benefits of restoration projects on listed species.
Matrix of interactions among proposed restoration actions and across all species.
Compilation of species accounts with scientific information from species experts.

Figure 3. Goal, objectives, and information needs for efforts on threatened and endangered species.

Issues

The Okeechobee gourd (*Cucurbita okeechobeensis*), a wetland species, is the only Federally endangered plant likely to be affected by water management activities associated with restoration of the Everglades. The effects on individuals and habitat of this species would need to be considered and mitigated wherever it is present in areas to be modified by restoration.

All the other species are plants of upland areas (principally scrub and pine rocklands) and beaches not likely to be altered by restoration activities. Acquisition of scrub tracts in the Lake Wales Ridge NWR is essential. Fire management of those tracts and other sites where listed plants and animals occur on the Lake Wales Ridge is being addressed in the FWS multispecies recovery plan. Management of pine rocklands in Dade County (particularly Federal lands in the Richmond area) is needed to ensure survival and recovery of the pine rockland plants. Fire management is of particular importance.

The Fakahatchee Strand in southern Collier County is a major enclave of rare wetland plants (but no current Federally listed species). Ponds and swamp forests in this area harbor about 25 species of epiphytic ferns, orchids, and bromeliads not found elsewhere in the U.S. Major hydrological changes in the Fakahatchee Strand during restoration should be avoided.

Reptiles and Amphibians

Background

The Federal list of endangered reptiles known to occur in South Florida includes four species of sea turtles (Atlantic green, leatherback, Atlantic hawksbill, and Atlantic ridley) and the American crocodile. Species listed as threatened are the Atlantic loggerhead sea turtle, Eastern indigo snake, Atlantic salt marsh snake, blue-tailed mole skink, sand skink, and American alligator (by similarity of appearance to the crocodile). No Federally listed species of amphibian occurs in South Florida. Sea turtles are restricted to coastal beaches, broad bays and lagoons, and offshore areas, while the crocodile is an estuarine species associated with undisturbed tracts of mangrove and lagoon habitats. The indigo snake is an upland species throughout South Florida. The skinks are associated with scrub habitat of the Lake Wales Ridge. Additional State-listed species include the threatened Miami black-headed snake and Big Pine Key ringneck snake and Lower Florida Keys populations of the striped mud turtle (considered endangered by the FGFWFC) and the Florida brown snake and Florida ribbon snake (both threatened).

Of the five species of sea turtles, two are known to nest regularly on beaches in one or more subregions. The loggerhead is a locally common nester on both Atlantic and Gulf Coast beaches, including Cape Sable and the Dry Tortugas (Davis and Whiting 1977; Williams and Dawson 1984), and the green turtle nests in limited but perhaps increasing numbers along the central and southern Atlantic Coast (Conley and Hoffman 1987). The leatherback and hawksbill may nest rarely at sites on the ocean side of the Keys. The loggerhead, green, and hawksbill regularly use seagrass beds, tidal channels, and reef tracts and patches as feeding habitat, including seagrass beds and channels in Florida Bay. The other two species, leatherback and ridley, are of very rare and uncertain status in the Region. Population trends by the nesting species are unknown because no long-term nest monitoring programs for all of the important nesting beaches in the Region have been maintained.

Issues

Sea turtles once were much more common in southern Florida estuaries, as indicated by the prevalence of a commercial sea turtle fishery in these waters between the 1850s and 1973 (Rebel 1974). The impacts on turtles of degradation of seagrass beds and coral reef communities remain unknown, in large part because of difficulties in estimating current populations and seasonal patterns from existing data. The continuing importance of these habitats, however, is suggested by a sample of sea turtles captured for tagging on banks in western Florida Bay in 1990 and 1991, which consisted of 51 loggerheads, 23 greens, and one hawksbill (mostly subadults; S. Snow, pers. comm.). Hawksbills are more common around reefs and ocean creeks in Biscayne and Dry Tortugas National Parks (Robertson 1989a).

The American crocodile has disappeared from most of its former range in Biscayne Bay and the Florida Keys. Viable nesting subpopulations now occur only in eastern and northern Florida Bay as far west as the Cape Sable peninsula, on northern Key Largo, and in the Turkey Point Nuclear Power Plant cooling canals (Kushlan and Mazzotti 1989a; Ogden 1978). Mazzotti (1994) showed, although the number of nesting females in ENP has been stable or slowly increasing during the past decade, the number nesting in traditional creek habitats in northeastern Florida Bay has declined. It is not known whether the decline in the number of creek nests is due to some as yet undiscovered environmental change that has occurred in this area (Mazzotti and Brandt 1989). Although the crocodile is the best studied and monitored of South Florida's listed species of reptiles (Kushlan and Mazzotti 1989b; Mazzotti 1989; Moler 1991), the facts that a major segment of the nesting population occurs downstream from the degraded Taylor Slough/C-111 basins and relationships between crocodile distribution and salinity remain poorly known demand close attention be given to this species during the restoration process. Mazzotti and Brandt (1995) suggested hatchling crocodiles in northeastern Florida Bay may be sensitive to increases in salinity levels.

Although the indigo snake remains widespread in pinelands and hammocks throughout southern Florida, little is known of population trends (Dalrymple 1988; Robertson 1989b; Steiner et al. 1983). Subpopulations are expected to remain secure on well protected, public lands but may decline where habitat alteration and collecting occur. Continued loss of scrub habitat in Central Florida is the major threat to the sand and blue-tailed mole skinks.

Current studies

Except for sea turtle nest monitoring projects on several public beaches in South Florida, conducted largely by volunteers, no organized scientific study of sea turtles is presently in place. Most known crocodile nests at Turkey Point, northern Key Largo, and ENP are monitored annually for measures of activity and success. No current studies of indigo snake are known.

Information needs

Ecosystem restoration in the Everglades basin should benefit the regional reptile populations, or at worst should have no negative impacts. In order to assure this goal is achieved, restoration planning must be based on adequate information on the ecology and distribution of these populations in South Florida. Critical needs are to:

- Determine relationships between crocodile distribution, nesting patterns and success, survival of age classes, and salinity.

- Continue and expand the long-term monitoring program for crocodile nesting in South Florida.

- Implement nesting censuses for sea turtles, using standard sea turtle nest census protocols, on beaches in ENP and Dry Tortugas National Park and elsewhere as required to compare with earlier nesting studies.

- Determine condition and relative importance of sea turtle feeding habitats in Florida Bay and waters adjacent to the Upper Florida Keys and develop a GIS model of juvenile habitats.

- Conduct satellite telemetry of green turtles nesting in South Florida to determine migration patterns and marine/estuarine areas critical to their survival.

- Determine the frequency and range of dispersal of raccoons on beaches and between islands to more effectively target programs to control predation on sea turtle nests.

- Expand existing studies on effects of beach renourishment projects on sea turtle nesting, including possible effects of depositing imported aragonite sand on Florida beaches.

Birds

The Federal list of birds in South Florida includes eight endangered species (Cape Sable seaside sparrow, Florida grasshopper sparrow, ivory-billed woodpecker, Kirtland's warbler, wood stork, red-cockaded woodpecker,

snail kite, Bachman's warbler) and five threatened species (Florida scrub jay, Audubon's crested caracara, bald eagle, piping plover, roseate tern). Restoration of predrainage patterns of freshwater flow into the Kissimmee River, through Lake Okeechobee, and south through the Everglades to the estuaries should benefit the wood stork, Cape Sable seaside sparrow, and snail kite, but it will have uncertain effects on the bald eagle and Florida grasshopper sparrow. Proper management of old growth pine forests and xeric oak scrub will probably have the greatest benefit for the red-cockaded woodpecker and Florida scrub jay. Current range management practices appear to be compatible with habitat requirements of Audubon's crested caracara; however, conversion of wetlands to citrus and row crops poses a threat to this species as well as to all freshwater-dependent species.

Several additional species of birds are listed by the FGFWFC, FNAI, and FCREPA. The State lists include a number of wetland species, most listed as species of special concern by the FGFWFC, that are dependent on freshwater and estuarine habitats likely to be directly influenced by hydrologic restoration. Protection of tropical hardwood hammocks on the mainland and in the Florida Keys is the largest factor influencing the status of the white-crowned pigeon (listed as threatened by the FGFWFC). In addition, several migratory species are dependent on South Florida coastal areas. These include the Arctic peregrine falcon (listed as endangered by the FGFWFC), southeastern American kestrel (threatened), and southeastern snowy plover (threatened), which migrate through the Region and winter in coastal areas.

Following are expanded discussions of issues and information needs for selected species:

Cape Sable seaside sparrow

Background. Cape Sable seaside sparrows occur in freshwater prairies bordering the southern Everglades (Bass and Kushlan 1982; Curnutt and Pimm 1993; Werner 1976;). Populations on Cape Sable and in the Ochopee area have been greatly reduced or extirpated apparently because of habitat alterations. Currently most of the population is divided between the east and west flanks of Shark Slough and across high-elevation marshes bordering the upper Taylor Slough. Kushlan et al (1982) summarized current knowledge of the spatial relations, movement, and breeding biology of Cape Sable seaside sparrows. These sparrows nest in discreet subpopulations that are patchily distributed across short-hydroperiod marshes.

Issues. Although distribution and density of nesting birds are affected by pattern and seasonality of water coverage and by frequency and distribution of fires, these relationships have been only superficially measured.

Current studies. J. Curnutt and S. Pimm, University of Tennessee, are investigating relationships between Cape Sable sparrow populations and hydrological and burning patterns in the marshes. Annual censuses of the total Cape Sable sparrow population have been conducted since 1992 by ENP.

Information needs.

- Develop better definition of habitat requirements for this species in terms of fire frequency and hydrology in both the Taylor Slough and southern Big Cypress basin. Annual censuses of distribution and density of the sparrows, relative to fire and water conditions, are required.

- Develop a critically needed understanding of dispersal and colonization ability of both adult and young sparrows. Radiotelemetry studies of adults and young should be undertaken to determine movement patterns of individual birds.

- Develop improved understanding of habitat requirements and the reasons for patchy distribution in order to develop restoration plans that will maintain this species as hydrological conditions change during the restoration process.

- Conduct detailed color-marking study of one colony to determine aspects of demography such as dispersal patterns relative to age and sex, survivorship, and effects of fire on distribution.

Snail kite

Background. The snail kite population in Florida currently numbers between 700 and 1,000 individuals (R. Bennetts, pers. comm.). Annual censuses have been conducted since the late 1960s, providing a relatively long record of population changes (Rodgers et al. 1988). The current number represents recovery from a population that may have been as low as a few dozen birds during the late 1950s and early 1960s.

Issues. Although snail kites feed almost exclusively on apple snails, the environmental dynamics of snail populations are only poorly understood. This is in large part because of difficulties in measuring snail numbers, densities, and survival patterns.

Current studies. Bennetts is investigating several aspects of snail kite biology and population dynamics crucially important to restoration planning. The studies include relationships between kite dispersal, reproductive patterns, and hydrological variables (water depth and drying patterns) and effects of dispersal on mortality and reproductive patterns. This study, now in its fourth year and faced with funding cuts, is showing that kites have greater than expected dispersal and survival rates and wider habitat tolerances than previously suspected (Beissinger 1988; Beissinger and Takekawa 1983; Bennetts et al. 1988, 1994). The study also will describe an improved census protocol for snail kites that will measure kite population trends more accurately than has been possible with past censuses.

Information needs.

- Continue detailed ecological studies of the response of kites to changing water conditions in South Florida, to take advantage of the large number of birds currently carrying functional radio transmitters. Maintain monitoring and reproductive studies of breeding populations of snail kites throughout their Florida range.

- Conduct a study of the ecology of apple snails and what conditions make them available to snail kites.

- Implement an improved census program that more accurately estimates populations of kites.

Wood stork

Background. Wood storks are highly social birds, nesting in colonies and feeding in flocks. Historically, between 2,500 and 4,000 pairs nested in large colonies in ENP, and as many as 10,000 pairs nested in the Big Cypress (Ogden 1994). Numbers nesting in these two areas have greatly declined, primarily since the early 1960s, to less than 250 pair in ENP and less than 500 pairs in Big Cypress. Historically, South Florida was the most important nesting area for the southeastern U.S. population of wood storks (Ogden and Nesbitt 1979; Ogden et al. 1987). It is no longer important as a nesting area but still remains extremely important as a winter and spring foraging area for storks that subsequently migrate north (Bancroft et al. 1992). Breeding storks have responded to deterioration of the Everglades/Big Cypress area by shifting colony locations into northern Florida, Georgia, and South Carolina.

Issues. A major factor responsible for the population decline has been a substantial delay in the timing of nesting since the 1960s in both ENP and Big Cypress colonies, which has resulted in a sharp decline in nesting success. Delayed nesting is thought to have been caused by loss of foraging habitat during the early and middle dry seasons. This has forced birds to delay nesting until the deeper central sloughs dry during the late dry season. It has been hypothesized that those critical, early dry season foraging habitats were located in either the higher elevation freshwater marl prairies that flank the deeper sloughs or in the broad mainland estuaries bordering northern Florida Bay and the southwestern Gulf Coast, or both (Robertson and Frederick 1994). Habitat changes that have reduced production, survival, and availability of fishes as prey (Ogden et al. 1976) for storks in these two habitats have not been measured. It is widely considered that these habitat changes have been caused by unnatural hydrological patterns.

Current studies. Except for annual censuses of nesting colonies, no wood stork studies are currently active.

Information needs.

▸ Conduct a detailed demographic study of storks nesting in the Everglades basin to better quantify aspects of recruitment and adult and juvenile survivorship related to late nesting.

▸ Conduct a detailed study of the effects of mercury, other toxins, and parasites on survivorship and reproductive success of wood storks.

▸ Perform an analysis of factors that determine when and where wood storks forage and nest. The Systematic Reconnaissance Study data set in combination with colony and historical survey data should be used to look at relationships between timing and location of colonies and regional hydrological patterns. An important part of this study would be to document what appear to be changing relationships between stork nesting patterns and regional hydropatterns, which presumably reflect fundamental changes in the way the Everglades system operates at primary and secondary production levels.

Bald eagle

Background. In Florida, bald eagles nest in riparian, lake, and coastal areas. Eagles feed on a wide variety of vertebrate prey, which is primarily fish but includes birds and turtles (Robertson 1989c). Eagles generally initiate nesting in October-November, and young fledge in mid- to late spring. Many individuals, especially young, disperse north during the summer. Pairs are permanently territorial and often will repeatedly use the same nest for a number of years.

Issues. An issue that needs to be resolved is why the breeding population of eagles in Florida Bay has been relatively stable since the 1950s (W. Robertson, NBS, pers comm.), while the osprey population (also fish eaters) in the Bay has declined.

Current studies. Bald eagle nests in Florida Bay and along the Gulf Coast of ENP are monitored annually by W. Robertson.

Information needs.

▸ Conduct a detailed study to look at distribution and possible impacts of mercury on bald eagles.

▸ Perform radio tracking and/or satellite tracking of juvenile and adult eagles nesting in ENP and the Florida Keys to determine annual movement patterns related to habitat requirements, especially during nonbreeding periods.

▸ Continue, and expand as needed, monitoring of nesting bald eagles throughout the ENP, Big Cypress, and Florida Keys.

Red-cockaded woodpecker

Background. In Florida, red-cockaded woodpeckers occur as scattered populations in mature pinelands throughout the peninsula as far south as the southern Big Cypress area; they formerly occurred in the Long Pine Key pinelands of ENP (Robertson 1989d). This species excavates nesting and roosting cavities only in older living pines; generally these trees are only available in old growth stands. Local populations maintain cohesive social groups, which operate as discrete resident units throughout the year. Each "clan" maintains several cavity trees and may take more than one year to fully excavate each tree (Baker 1971). Red-cockaded woodpeckers disappeared from the pinelands of southern Dade County, including those in ENP, between 1935-1965, associated with logging and urban/agricultural development (Robertson 1989d). Although small colonies in the Big Cypress continue to survive, the number of birds has been slowly declining. Also, some cavity trees in the southern Big Cypress were damaged by Hurricane Andrew (D. Jansen, pers. comm.).

Issues. The major conservation issues for this woodpecker in South Florida are: 1) the status and preservation of the Big Cypress population, and 2) the possibility of reintroducing the species into pine forests of Long Pine Key in ENP.

Current studies. Reports on red-cockaded woodpecker censuses (D. Jansen) and research (K. Meyer) in BCNP are in preparation.

Information needs.

- Expand the ecological and distributional survey of the Big Cypress population. Distributional surveys of clans within BCNP and the Addition area need to be completed and maintained. The survey area should be expanded to include surrounding pinelands not in Federal ownership that may contain woodpeckers or could have them reintroduced.

- Perform ecological studies of the Big Cypress population to better measure habitat requirements, survivorship, dispersal capabilities, movement patterns, and population viability.

- Conduct survey of areas where red-cockaded woodpeckers may be able to be reintroduced, including Long Pine Key.

White-crowned pigeon

Background. In the U.S., the white-crowned pigeon occurs primarily from the southern tip of the Florida peninsula south through the Florida Keys. This tropical pigeon is most abundant in May-September when it breeds on mangrove keys from Biscayne Bay south. Major nesting concentrations occur in Florida Bay and the Great White Heron and Key Deer NWRs (Bancroft et al. 1994). Nesting distribution appears limited by the presence of raccoons and other nest predators. Pigeons make daily flights to tropical hardwood forests to feed (Strong et al. 1994). During the breeding season, they feed primarily on the fruits of poisonwood, blolly, shortleaf fig, strangler fig, and black torch.

Issues. The greatest threat to this species in the U.S. is continued destruction of tropical hardwood forests. Expansion of raccoons and disturbance of birds on nesting islands by humans continue to decrease availability of safe nesting areas. Most white-crowned pigeons from Florida winter in the Bahamas or Greater Antilles and little is known about their wintering ecology or migratory behavior.

Current studies. No white-crowned pigeon projects are currently active.

Information needs.

- Purchase and protect all remaining tropical forest parcels larger than 5 ha (12 acres) from Key Largo south to Key West. Complete the North Key Largo, Tropical Flyways, Big Pine/Coupon Bight, and Lower Keys Hammocks CARL projects. Complete Federal acquisition of lands in Crocodile Lake and Key Deer NWRs.

- Conduct comprehensive censuses of pigeon nesting and feeding habitats in the lower Florida Keys.

Mammals

Background

Seven species of mammals Federally listed as endangered occur in South Florida: Florida panther, Key deer, Key Largo cotton mouse, Key Largo woodrat, Lower Keys marsh rabbit, silver rice rat, and West Indian manatee. One species, the southeastern beach mouse, is listed as threatened.

The panther occurs throughout the Big Cypress and freshwater portions of the western Everglades, mainly in upland woodlands. The manatee is primarily coastal but also moves into canals and rarely into Lake Okeechobee.

The beach mouse occurs only in areas of undisturbed dunes and is most likely restricted to St. Lucie County. The five remaining species are restricted to the Florida Keys. In addition to the Federal list, the FGFWFC lists the Florida mastiff bat as endangered in the State and the Everglades mink, Big Cypress fox squirrel, and Florida black bear as threatened.

The Florida panther has been much more intensively studied than any other endangered mammal in South Florida (Alvarez 1993; Belden 1988; FWS 1987; McBride 1985; Smith and Bass 1994). These reports show, although upland forests are the preferred panther habitat in South Florida, animals often include large areas of aquatic habitats within hunting ranges. However, extensive wetlands may limit panther movements, as has been suggested by observations that panthers are more likely to cross Shark Slough during extended dry periods (O. Bass, pers. comm.). In addition, white-tailed deer, the panther's primary natural prey, also tend to move out of Everglades marshes during periods of deeper flooding (Fleming 1991). These observations suggest water depth and distribution patterns may influence panther distribution patterns, either directly or by affecting prey patterns.

The strongest population trend database for manatee from the southern Everglades subregions is based on aerial censuses conducted in the Gulf Coast estuaries and Florida Bay portion of ENP in a number of years during 1973-1993 (Beeler and O'Shea 1988, Snow 1993). Although these censuses showed the highest total numbers in 1991 (1,451) and 1992 (1,585), relative declines occurred in two areas -- Whitewater Bay and northern Florida Bay -- where salinities may have increased as a result of reduced flows from the Everglades. These censuses seem to support the preliminary conclusion that "to some degree" movements and aggregations of manatees can be correlated with distribution of seagrasses and vascular freshwater aquatic vegetation (Hartman 1974).

Issues

In spite of the number of studies on panther in South Florida, relationships between prey abundance and distribution and hydrological parameters are either poorly known or poorly reported. It is possible restoration of Everglades wetlands may adversely impact the panther by reducing the total area of habitat suitable to panthers or white-tailed deer and by further isolating any remaining animals in the subpopulation that may still occur east of Shark Slough.

The relationships between manatees and aquatic vegetation and salinity patterns remain poorly understood. The censuses also show seasonal patterns of movements and distribution that have yet to explained by environmental correlations. Many other aspects of the biology and ecology of manatee in South Florida have not been studied. It is not suspected that ecosystem restoration will have a major effect on manatee. Reduced salinities in South Florida estuaries may even create better foraging habitat conditions.

Continued survival or recovery of endangered species populations in the Florida Keys will depend on preservation of adequate amounts of upland habitat (for Key deer, cotton mouse, woodrat) and wetland habitat (for marsh rabbit and rice rat in the Lower Keys). Survival of the southeastern beach mouse will depend on preservation of undisturbed beach habitat. The status of several State-listed species, such as the Big Cypress fox squirrel, remain poorly known (Humphrey 1992).

Current studies

Except for monitoring of panther, primarily in the Big Cypress subregion, and annual State-coordinated manatee censuses, no mammal studies are known.

Information needs

- Continue long-term censuses of manatees to measure distribution and abundance.

- Develop benthic vegetation maps for ENP to interpret manatee movement and distribution patterns.

- Determine the ecological and physiological freshwater requirements of the manatee. Use telemetry to address movement patterns related to hydrological parameters.

▸ Analyze existing food habits data for the panther, relative to effects of hydrological patterns on distribution and abundance of prey species.

▸ Produce a life history table for the Florida panther, including better estimates of current population size, carrying capacity, dispersal, mortality, and reproduction. This will allow improved risk assessment for use in determining a jeopardy threshold for projects affecting panther habitat.

▸ Determine the status of the Big Cypress fox squirrel and round-tailed muskrat.

BIBLIOGRAPHY

Alvarez, K. 1993. Twilight of the Panther. Myakka River Publishing, Sarasota, Florida. 501 pp.

Baker, W.W. 1971. Progress report on life history studies of the Red-cockaded Woodpecker at Tall Timbers Research Station. Pages 44-59 *in* R.L. Thompson, editor. The ecology and management of the red-cockaded woodpecker. Tall Timbers Research Station, Tallahassee, Florida.

Bancroft, G.T., R. Bowman, R.J. Sawicki, and A.M. Strong. 1994. Relationship between the reproductive ecology of the white-crowned pigeon and the fruiting phenology of tropical hardwood hammock trees. Technical Report. Nongame Wildlife Program, FGFWFC, Tallahassee, Florida.

Bancroft, G.T., W. Hoffman, R.J. Sawicki, and J.C. Ogden. 1992. The importance of the Water Conservation Areas in the Everglades to the endangered wood stork (*Mycteria americana*). Conservation Biology 6(3):392-398.

Bass, O.L. Jr., and J.A. Kushlan. 1982. Status of the Cape Sable sparrow. Report T-672. SFRC, ENP, Homestead, Florida. 41 pp.

Beeler, I.E., and T.J. O'Shea. 1988. Distribution and mortality of the West Indian manatee (*Trichechus manatus*) in the southeastern United States: a compilation and review of recent information. Volume One: The Atlantic coast. Report No. 88-09. FWS, National Ecology Research Center, Gainesville, Florida.

Beissinger, S.R. 1988. Snail kite *Rostrhamus sociabilis*. Pages 148-165 *in* R.S. Palmer, editor. Handbook of North American Birds, Volume 4. Yale University Press, New Haven.

Beissinger, S.R., and J.E. Takekawa. 1983. Habitat use and dispersal of snail kites in Florida during drought conditions. Florida Field Naturalist 11:89-106.

Belden, R.C. 1988. The Florida panther. Pages 515-532 *in* W.J. Chandler, editor. Audubon Wildlife Report 1988/1989. NAS, New York.

Bennetts, R.E., M.W. Collopy, and S.R. Beissinger. 1988. Nesting ecology of snail kites in Water Conservation Area 3A. Florida Cooperative Fish and Wildlife Research Unit, Gainesville, Florida. 174 pp.

Bennetts, R.E., M.W. Collopy, and J.A. Rodgers, Jr. 1994. The Snail kite in the Florida Everglades: a food specialist in a changing environment. Pages 507-532 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Conley, W.J., and B.A. Hoffman. 1987. Nesting activity of sea turtles in Florida, 1979-1985. Florida Scientist 50:201-210.

Curnutt, J.L., and S.L. Pimm. 1993. Status and ecology of the Cape Sable seaside sparrow. Contract 5280-2-9021. FWS, Jacksonville, Florida.

Dalrymple, G.H. 1988. The herpetofauna of Long Pine Key, Everglades National Park, in relation to vegetation and hydrology. Manuscript. 74 pp.

Davis, G.E., and M.C. Whiting. 1977. Loggerhead sea turtle nesting in Everglades National Park. Herpetologica 33:18-28.

Fleming, D.M. 1991. Wildlife ecology studies. 1991 annual reports. Volume 1, Section 5. SFRC, ENP, Homestead, Florida.

Hartman, D.S. 1974. Distribution, status, and conservation of the manatee in the United States. FWS, National Fish and Wildlife Laboratory, Gainesville, Florida. NTIS PB81-140725. 247 pp.

Humphrey, S.R, editor. 1992. Mammals. Volume 1. Rare and Endangered Biota of Florida. University Presses of Florida, Gainesville. 392 pp.

Kushlan, J.A., O.L. Bass Jr., L.L. Loope, W.B. Robertson Jr., P.C. Rosendahl, and D.L. Taylor. 1982. Cape Sable sparrow management plan. Report M-660. SFRC, ENP, Homestead, Florida. 37 pp.

Kushlan, J.A., and F.J. Mazzotti. 1989a. Historic and present distribution of the American crocodile in Florida. Journal of Herpetology 23:1-7.

Kushlan, J.A., and F.J. Mazzotti. 1989b. Population biology of the American crocodile. Journal of Herpetology 23:7-21.

Mazzotti, F.J. 1989. Factors affecting the nesting success of the American crocodile, *Crocodylus acutus*, in Florida. Bulletin of Marine Science 44:220-228.

Mazzotti, F.J. 1994. Status and trends of nesting of the American crocodile in Everglades National Park, Florida. Final report to the COE and NPS. 26 pp.

Mazzotti, F.J., and L.B. Brandt. 1989. Evaluating the effects of groundwater levels on the reproductive success of the American crocodile in Everglades National Park. Final report. Florida Cooperative Fish and Wildlife Unit, Gainesville, Florida.

Mazzotti, F.J., and L.A. Brandt. 1995. A biological assessment of the effects of the C-111 project on the American crocodile in northeastern Florida Bay, Everglades National Park. Department of Wildlife Ecology and Conservation, UF, Gainesville, Florida.

McBride, R. 1985. Population status of the Florida panther in the Everglades National Park and Big Cypress National Preserve. Final report. ENP, Homestead, Florida. 57 pp.

Moler, P.E. 1991. American crocodile population dynamics. Final report. FGFWFC, Tallahassee, Florida.

Moler, P.E., editor. 1992. Amphibians and Reptiles. Volume III, Rare and Endangered Biota of Florida (P.C.H. Pritchard, series editor). University Presses of Florida, Gainesville. 291 pp.

Ogden, J.C. 1978. Status and nesting biology of the American crocodile, *Crocodylus acutus* (Reptilia, Crocodylidae), in Florida. Journal of Herpetology 12:183-196.

Ogden, J.C. 1994. A comparison of wading bird nesting colony dynamics (1931-1946 and 1974-1989) as an indicator of ecosystem conditions in the southern Everglades. Pages 533-570 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Ogden, J.C., J.A. Kushlan, and J.T. Tilmant. 1976. Prey selectivity of the wood stork. Condor 78:324-330.

Ogden, J.C., D.A. McCrimmon Jr., G.T. Bancroft, and B.W. Patty. 1987. Breeding populations of the wood stork *Mycteria americana* in the southeastern United States. Condor 89:752-759.

Ogden, J.C., and S.A. Nesbitt. 1979. Recent wood stork population trends in the United States. Wilson Bulletin 91:512-523.

Orians, G.H., M. Bean, R. Lande, K. Loftin, S. Pimm, R.E. Turner, and M. Weller. 1992. Report of the Advisory Panel on the Everglades and Endangered Species. Audubon Conservation Report No. 8. NAS, New York.

Rebel, T.P. 1974. Sea turtles and the sea turtle industry of the West Indies, Florida, and the Gulf of Mexico. University of Miami Press, Miami, Florida. 236 pp.

Robertson, W.B. Jr. 1989a. Hawksbill turtle. Manuscript. ENP, Homestead, Florida. 5 pp.

Robertson, W.B. Jr. 1989b. Eastern indigo snake. Manuscript. ENP, Homestead, Florida. 4 pp.

Robertson, W.B. Jr. 1989c. Bald eagle. Unpublished manuscript. SFRC, ENP, Homestead, Florida.

Robertson, W.B. Jr. 1989d. Red-cockaded woodpecker. Unpublished manuscript. SFRC, ENP, Homestead, Florida.

Robertson, W.B. Jr., and P.C. Frederick. 1994. The faunal chapters: contexts, synthesis, and departures. Pages 709-737 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Rodgers, J.A. Jr., S.T. Schwikert, and A.S. Wenner. 1988. Status of the snail kite in Florida: 1981-1985. American Birds 42:30-35.

Smith, T.R., and O.L. Bass Jr. 1994. Landscape, white-tailed deer, and the distribution of Florida panthers in the Everglades. Pages 693-708 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Snow, S. 1993. The Florida manatee in Everglades National Park. Manuscript. ENP, Homestead, Florida.

Steiner, T.M., O.L. Bass Jr., and J.A. Kushlan. 1983. Status of the Eastern indigo snake in southern Florida national parks and vicinity. Report 83/01. SFRC, ENP, Homestead, Florida. 25 pp.

Strong, A.M., R.J. Sawicki, and G.T. Bancroft. 1994. Estimating white-crowned pigeon population size from flight-line counts. Journal of Wildlife Management 58:156-162.

U.S. Fish and Wildlife Service. 1987. Florida panther recovery plan. Southeastern Region, FWS, Atlanta, Georgia.

Ward, D.B., editor. 1978. Plants. Volume 5, Rare and Endangered Biota of Florida (P.C.H. Pritchard, series editor). University Presses of Florida, Gainesville.

Werner, H.W. 1976. Distribution, habitat, and origin of the Cape Sable seaside sparrow. M.S. Thesis, University of South Florida, Tampa, Florida. 53 pp.

Williams, D.E., and R.H. Dawson. 1984. Sea turtle monitoring study. Fort Jefferson National Monument, Dry Tortugas, Florida. Project report to FWS, Jacksonville, Florida. 22 pp.

Wood, D.A. 1994. Official lists of endangered and potentially endangered fauna and flora in Florida. FGFWFC, Tallahassee, Florida.

HARMFUL NONINDIGENOUS SPECIES

INTRODUCTION

Nonindigenous species are those not native to a specific area and introduced by humans. They are sometimes referred to as non-native species or exotic species. Some are considered pest, nuisance, harmful, or invasive species. Schmitz and Brown (1994) refer to these species as "anthropogenic pollution."

Invasion by nonindigenous species originating from throughout the tropical-subtropical world is a major threat to South Florida natural areas. Many nonindigenous plant and animal species have escaped cultivation and become established in the Region. Nonindigenous plants and land animals constitute about 25% of all species in the State as a whole (OTA 1993). Some have not only colonized disturbed sites but also invaded natural lands set aside for preservation of natural communities and landscapes. South Florida itself probably has more problems with aggressive nonindigenous species than any other entire State.

Economic, as well as ecologic, problems arise from invasions by nonindigenous species. Many agricultural pests, marine fouling organisms, and aquatic weeds are nonindigenous species. Loss, through exotics infestations, of the natural characteristics that draw visitors to South Florida from all over the world can be expected to result in further economic losses.

Problems caused by invasive nonindigenous plant species are particularly noticeable. Florida as a whole has approximately 925 established nonindigenous plant species growing outside of cultivation (OTA 1993). Over 100 of these are listed as invasive in Florida by the Florida Exotic Pest Plant Council (FLEPPC 1995). Melaleuca (*Melaleuca quinquenervia*) and Brazilian pepper (*Schinus terebinthifolius*) are well-known examples of harmful nonindigenous trees that are widespread and expanding their coverage in South Florida. At least 23 nonindigenous plants are now found in Florida waters (McCann et al. 1995).

Many nonindigenous animal species have become established in Florida's aquatic systems: 83 fish, at least 26 insects since 1970, 2 amphibians, 3 birds, 1 mammal, 1 reptile, 5 mollusks, 1 crustacean, and an unknown number of pathogens (McCann et al. 1995). Many nonindigenous terrestrial animals, particularly birds, reptiles, and amphibians, have escaped captivity and are reproducing in South Florida (McCann et al. 1995; Robertson and Frederick 1994). Of the introduced nonindigenous bird species in the continental U.S., 63% are in Florida. Florida also has the largest number of established nonindigenous amphibians and reptile species in the U.S. (OTA 1993).

Insects undoubtedly are the most numerous animal immigrants to Florida. At least 946 arrived without purposeful human help, often as hitchhikers on cargo, especially plants (Frank and McCoy 1994). The best-known problem insects are those that have caused harm to humans and economic crops. Those that harm natural systems are less known, but could be numerous. A recent concern is the weevil *Metamasius callizona*, which kills all three of Florida's native bromeliad genera (*Tillandsia*, *Catopsis*, and *Guzmania*) in natural areas (Frank and Thomas 1994). This insect appears to be expanding fast, and there is concern it may soon reach the Fakahatchee Strand, an important area for conservation of native bromeliads (J. Frank, UF, pers. comm.).

South Florida is particularly vulnerable to invasion by nonindigenous species for a variety of reasons (Simberloff 1994), including insularity and the extent of habitat disturbance by humans. Coupled to this are South Florida's mild, generally frost-free climate, which makes it a mecca for persons growing tropical plants and animals, either commercially or as a hobby. Furthermore, Miami is port of entry for plants and animals arriving in the U.S. from all over the world. Of all plant shipments into the Nation, 85% pass through Miami (Simberloff 1994).

BACKGROUND

Description of the Problem

Nonindigenous plants negatively impact native habitats by outcompeting natives, decreasing species diversity, and altering topography and soils. Nuisance plants significantly reduce available native habitat for several Federal endangered species. Dense monocultures formed by melaleuca replace native vegetation and thus decrease nesting and foraging habitats for endangered species such as the snail kite and Cape Sable seaside sparrow.

Aquatic plants such as hydrilla (*Hydrilla verticillata*), water lettuce (*Pistia stratiotes*), and water hyacinth (*Eichhornia crassipes*) clog streams, rivers and lakes. These aquatic weeds create a continual problem by obstructing navigable waterways throughout the Kissimmee-Okeechobee-Everglades system. Millions of dollars and extensive labor are spent each year to reduce these impediments. Herbicides are frequently used to prevent clogging of waterways and lakes. Therefore prolific nonindigenous plants are indirectly responsible for the application of tons of chemicals to Florida waters.

Prolific animal species that have escaped to the wild may degrade habitat quality for native wildlife, introduce diseases or pathogens, or outcompete or prey on native species. In many locations non-native herpetofauna (e.g., *Anoles segrii*) have replaced native congenitors (e.g., *Anoles carolinensis*). Cichlid fish species have invaded ENP and appear as dominants of the aquatic fish community in visitor areas such as the Anhinga Trail. Cichlids also are common components of the brackish-water fish community in coastal areas of the Park adjacent to northeastern Florida Bay (Lorenz 1993).

The escape from captivity of nonindigenous fish is a particular concern because of Florida's extensive, unique, internationally recognized wetlands. South Florida's low natural diversity of freshwater fishes is one factor that has made it vulnerable to invasion by nonindigenous fish. South of Lake Okeechobee, nonindigenous species already make up over 50% of the inland fish fauna (Courtenay 1994a). Disturbance enhances establishment of nonindigenous fish because they often are more tolerant of disrupted habitats than are native species. Because any fish species varies morphologically and ecologically at different stages of its life cycle, nonindigenous fish can affect native fish differently at each life stage. Invasive nonindigenous fish are a threat to native fish populations. Although there have not yet been any known extinctions, Warren and Burr (1994) concluded that the southeastern U.S. soon will equal or exceed the American west in the number of threatened and endangered fishes.

Non-native plant and insect pests in South Florida that attack economic crops, lawns, and golf courses have led to widespread application of pesticides for their control. For instance, infestation of turf grass by South American mole crickets (genus *Scapteriscus*) is a primary reason for the high pesticide applications on golf courses (Frank 1994). These pesticide applications degrade water quality and cause environmental damages.

Not all nonindigenous species are harmful. Many nonindigenous ornamental plant species never escape cultivation. Not even all species that spread beyond their planting site are invasive. In South Florida, however, the potential for harm to natural areas from even one invasive plant species is enormous. For instance, melaleuca, introduced in the early 1900s, now infests roughly 450,000 ac (703 mi^2) of South Florida to some degree (OTA 1993). At least 50,000-60,000 ac (78-95 mi^2) of melaleuca are growing as a monoculture (R. Doren, ENP, pers. comm.). Past experience and a study on the rate of expansion indicate the uncontrolled trees could overtake most of the remaining wetland areas south of Lake Okeechobee within 30 years (Bodle et al. 1994).

A virtually uncontrolled expansion of nonindigenous species is altering the South Florida landscape and affecting the functioning and biological integrity of the ecosystem. Melaleuca is just one example of the many species rapidly expanding in South Florida natural areas. Because the rate of expansion increases with time (Laroche and Ferriter 1992), it is important to control species such as melaleuca at early stages of infestation of a site. A coordinated, integrated multispecies science program is needed to develop information and techniques to control invasions by nonindigenous plants and animals that have already escaped cultivation and prevent introduction of new invaders. Lack of effective control efforts at early infestation stages is a major issue.

Existing Efforts

A comprehensive review and analysis of the effort to control harmful nonindigenous species recently was published by OTA (1993). Many needed science topics can be gleaned from that document, which includes a special section on Florida.

The FLEPPC is a nongovernmental group formed in 1984 to address the dilemma of invasive nonindigenous plants in Florida. One major activity of this group has been to develop an extensive, prioritized list of harmful nonindigenous plants. The present list includes 115 problematic nonindigenous species (FLEPPC 1995). The FLEPPC has a research committee whose responsibilities are to determine science priorities, facilitate funding coalitions, and review research proposals.

Progress has been made in developing effective methods for eradication of melaleuca on a local scale, and these methods are being applied in a coordinated effort in parts of South Florida. The Melaleuca Task Force was formed by several concerned entities that have joined together to systematically eradicate this species. As one of several working committees of the FLEPPC, the MTF is currently investigating and implementing several control operations and methods (MTF 1994).

Several State agencies are involved in nonindigenous plant control. The SFWMD leads several exotic eradication efforts in South Florida. The FDOT continually reduces and selectively maintains invasive nonindigenous plants on rights of way. The UF is conducting research on biological control of Brazilian pepper.

The FDEP has a long history of managing widespread invasive nonindigenous species on a regional basis. Its Aquatic Plant Management Program is based on maintenance control to reduce the requirements for chemical and other control efforts. Maintenance control, a concept that originated with the COE, is the process of maintaining a species at or below a prescribed percentage of cover (e.g., water hyacinth at 5%) through consistent efforts (Schmitz et al. 1993). This technique, applied to water hyacinth, substantially reduced herbicide usage and organic sedimentation. Because of maintenance control, water hyacinths now impact only 1000-1500 ac (1.5-2.3 mi^2) annually, compared to 120,000 ac (187 mi^2) in the 1960s (D. Schmitz, FDEP, pers. comm.). Maintenance control has also been effective with water lettuce, but not with hydrilla (Schmitz et al. 1993).

Federal agencies have many ongoing exotic control projects. The COE supports many exotic removal programs. The NPS is involved in control of melaleuca, Brazilian pepper, Australian pine (*Casuarina equisetifolia*), shoebutton ardisia (*Ardisia elliptica*), and other species in the National parks and preserves. The FWS is responsible for control of exotics in National wildlife refuges.

Local governments also have exotic removal efforts. County park and recreation agencies have concentrated on removing invasive non-native plants from natural areas throughout South Florida. Dade County has a multimillion dollar exotic control program to help tropical hammock areas in county parks recover from invasions by nonindigenous plants and some prolific native vines after Hurricane Andrew.

Several Federal laws deal with importation of nonindigenous species. The Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 and the Lacey Act authorize the FWS to issue regulations on aquatic and other nuisance species and restrict importations of exotic species. The APHIS also has responsibilities under the Lacey Act and administers the Federal Noxious Weed Act of 1974 and the Federal Plant Pest Act. Its responsibilities include identification of actual or potential noxious weeds and prevention of their entry into the U.S. (OTA 1993). These various laws as administered, however, have not been effective in preventing the importation of nonindigenous species potentially harmful to natural ecosystems (OTA 1993).

Only a few groups are actively involved in scientific investigation of nonindigenous species that threaten natural areas. In particular, these include the ARS, SFWMD, COE, and NPS. The SFWMD has established herbicidal evaluation plots on several invasive plant species throughout the Region. The NPS has conducted studies on methods to restore natural communities on rockplowed fallow farmland and prevent repeated reinvasions by nonindigenous species after their removal (Doren et al. 1990). The COE funds research on control of aquatic weeds and melaleuca. The ARS and UF are investigating various biological control organisms on several nonindigenous

plants, including melaleuca and Brazilian pepper. Host-specific organisms are tested for their effectiveness as control agents and for their general safety. The introduction of host-specific insects, such as seed and sapling eaters, can safely and economically decrease the spread of pest plants. Predatory insects, parasites, or pathogens can be used to control the spread of insect pests, if appropriate host-specific organisms can be found (e.g., see Frank 1994). Considerable progress has been made on identification and testing of a biological control agent for melaleuca. The proposed ARS quarantine facility in Fort Lauderdale will be used to expand investigations of the potential use of insects or plant pathogens to control or reverse expansion of invasive nonindigenous plants.

The Federal Interdepartmental Committee for Management of Noxious Weeds was formed recently and is made up of many agencies within the Departments of Interior, Transportation, Energy, and Agriculture. This group is responsible for coordinating noxious weed management. One objective is to reorient the emphasis of control efforts toward protecting natural lands and rangelands, not just croplands. This may eventually lead to allocation of more research dollars to the protection of natural areas.

Publication of the OTA report (1993) on harmful nonindigenous species was a major advancement because it provides an overview of the problem and the present institutional framework for addressing it, as well as an evaluation of program effectiveness. Problems specific to Florida were examined in a recent report by the FDEP (Schmitz and Brown 1994). The NPS is planning a similar report for its units.

Recently the COE (1995) completed a report that recommended the integrated use of mechanical, physical, biological, and chemical methods to control melaleuca. The exact combination of methodologies used at a given site will depend upon the treatment, population density of melaleuca to be removed, and status of the existing natural system. Several combinations of methods, including that proposed by Woodall (1980), currently are under review.

MAJOR ISSUES

The major issues in South Florida related to nonindigenous species are:

- Inadequacies in funding for scientific investigations that will lead to development of effective controls.
- Lack of funding to apply control methods to problem species.
- Delays and lack of consistency in responses to new problems.

Scientific study on exotic species in Florida has been underfunded, considering the magnitude of the problem and potential for further damage to the ecosystem. Most resources have been focused on agricultural pests and aquatic weeds. Little has been spent on investigations of exotic species that threaten natural areas.

Three interrelated lines of scientific inquiry are particularly needed:

- Studies to develop control technology.
- Basic biological and ecological studies to improve understanding of invasive exotic species.
- Screening and risk assessment technology.

With respect to control technology development, biological controls must be identified, tested, and distributed; environmental controls must be hypothesized and examined; mechanical or manual removal and herbicidal application strategies must be designed and applied and results of applications tested; and habitat restoration strategies must be treated as experiments in which follow-up data are collected and analyzed. Basic biological and ecological investigation is essential to the overall control effort. Such efforts will not only help develop greater understanding and perspective but also help design details of control methods; e.g., which biocontrol agents would be most effective, when to apply herbicides for maximum effectiveness. Screening and risk assessment technology could help focus control efforts on the greatest potential problems. All three lines of investigation are vitally important to the South Florida Ecosystem Restoration effort.

Biological control is a well-developed science. The simplest definition, paraphrased from Center et al. (1994), is "the introduction of a pest's own natural enemies (parasitoid, predator, or pathogen) from the pest's native

environment to a new environment in which the pest has become established." Biocontrol has been successfully applied to control of agricultural pests and aquatic weeds throughout the U.S. and in other parts of the world (Center et al. 1994). Recent successes include control of alligator weed in the southeastern U.S., including Florida. There is an extensive protocol to ensure a selected control agent will not only be effective against the chosen target but also will not affect nontarget organisms in the new environment. Biologic control is the possible means of control in certain cases (e.g., to control the Mexican weevil attacking native bromeliads (Frank and Thomas 1994).

Investigation of biological control, although it has made promising progress on several major invaders of South Florida natural areas, is inadequately funded, and other control methods alone cannot alone halt or reverse region-wide invasions. Biocontrol is an essential component of the control of melaleuca, Brazilian pepper, and other plant species already widespread in South Florida natural areas. Construction of the quarantine facility at Fort Lauderdale, an essential component of the ARS biological control program, is not yet fully funded nor are the staff and resources to operate the facility.

The limited amount of biological and ecological information concerning invasive species affects the ability to generate funding or devise control strategies. Scientific efforts are needed to address the following questions:

- How will water management alterations to restore the natural ecosystem affect nonindigenous plants and animals?
- What are the principal controls on expansion of an invasive nonindigenous species in its place of origin?
- What are the impacts of nonindigenous species on native species and ecosystems?
- What are the major factors influencing expansion rates of specific problem species in South Florida?
- What are the conditions that cause greatest stress to the invasive species at various life stages?
- What factors make a natural area susceptible to invasion by nonindigenous species?
- What are the seasonality of flowering, fruiting, and germination, as well as responses to environmental variables, that might allow a nonindigenous species to be controlled by management measures such as new water management or prescribed burning practices?
- How do nonindigenous plant species that establish monospecific stands affect the water budget? For instance, does melaleuca consume more water, particularly during the dry season, than the native species it replaces?

Addressing such questions would not only provide greater understanding for the need to control a species but would also provide insight to help design biological and environmental controls.

Science-based screening and risk assessment methods concerning invasive nonindigenous species are lacking, but they are needed to prioritize species so the greatest threats receive the most attention. Risk assessment methods would help focus control efforts by pinpointing generic invasive characteristics that could be used to screen proposed introductions and exclude those with high invasive potential. This would provide a scientific basis for banning the import of certain species before they become a problem rather than after.

Habitat restoration strategies are needed to prevent invasive nonindigenous plants from returning once they are removed from heavily infested areas. One general strategy is to replant native vegetation, but scientifically supported guidelines on how to most effectively reestablish native plant communities in South Florida are limited.

Horticultural approaches to control of nonindigenous species are poorly explored. The development and widespread dissemination of sterile varieties of popular, but invasive or potentially invasive, nonindigenous species might prevent future invasions by such species. Sterile cultivars are very popular in other regions; e.g., cottonless cottonwood trees, fruitless mulberry trees, and podless locust trees in the Southwest. The feasibility and potential long-term benefits of developing sterile cultivars is worth investigating.

In addition to their harmful effects on natural areas, many invasive nonindigenous species also are detrimental to agricultural lands. For instance tropical soda apple (*Solanum viarum*), a threat to natural areas, is becoming a serious agricultural problem in Florida. Even if controlled on agricultural lands, it will continue to reinvade unless infestations in natural areas also are curtailed. One recent immigrant, the weevil *Metamasius callizona*, that is threatening the survival of native Florida bromeliads, also attacks ornamental bromeliads and pineapple (Frank and Thomas 1994).

The role of nonindigenous animals in South Florida natural areas is so poorly documented that it is difficult to design and mount an effective effort to control those that are harmful to native plant and animal communities. The major issue, therefore, is the lack of meaningful information concerning the effect of nonindigenous animals on Florida's native ecosystems.

INFORMATION NEEDS

The information needs critical to control of nonindigenous species are shown in Figure 4 as related to the restoration and scientific objectives. The recommended approach includes the following:

▸ **Prepare coordinated science programs on invasive or otherwise harmful nonindigenous species for inclusion in the separate multispecies management plans for plants and animals recommended by the South Florida Ecosystem Restoration Interagency Working Group (1994).**

The first step in development of each science plan should be to prepare a comprehensive review of recent and ongoing studies. State agencies, particularly the FDEP and SFWMD, should be involved in the process, as should FLEPPC. The programs should take a long-term view toward the problem of invasive nonindigenous species in South Florida and consider the problem in the context of the South Florida Restoration effort. Efforts should not be restricted to only studies of individual species, but rather should attempt to build a set of principles that helps support a holistic, ecosystem approach to exotics control. The questions listed under Major Issues above should be addressed.

▸ **Continue and expand investigations of biological control.** (Suggested lead--ARS, COE)

These must include:

- Foreign exploration - search for the most effective control species in the species' native land.
- Overseas screening process - determine the most effective and safest species before importing to the U.S.
- Quarantine follow up - clearance for field release.
- Onsite field sites - colonization in areas affected.
- Assessment of success and performance of introduced control species.
- Technology transfer - distribution of organism throughout range of invasive species.

The quarantine facilities in Fort Lauderdale and Gainesville are critical components of the biological control effort. Funding must be provided to construct and operate the quarantine facility at Fort Lauderdale, improve and maintain the quarantine facilities in Gainesville, and provide support personnel for the Fort Lauderdale facility. Priority in biological control studies should be given to the greatest threats.

▸ **Conduct studies to develop ecological understanding of invasive nonindigenous species.** (Suggested lead--NBS)

With respect to nonindigenous plants, more work is needed to determine:

- Factors that affect invasibility of natural areas.
- Environmental requirements and phenology of each problem species as these relate to their vulnerability to specific prescribed burning or water management regimes.

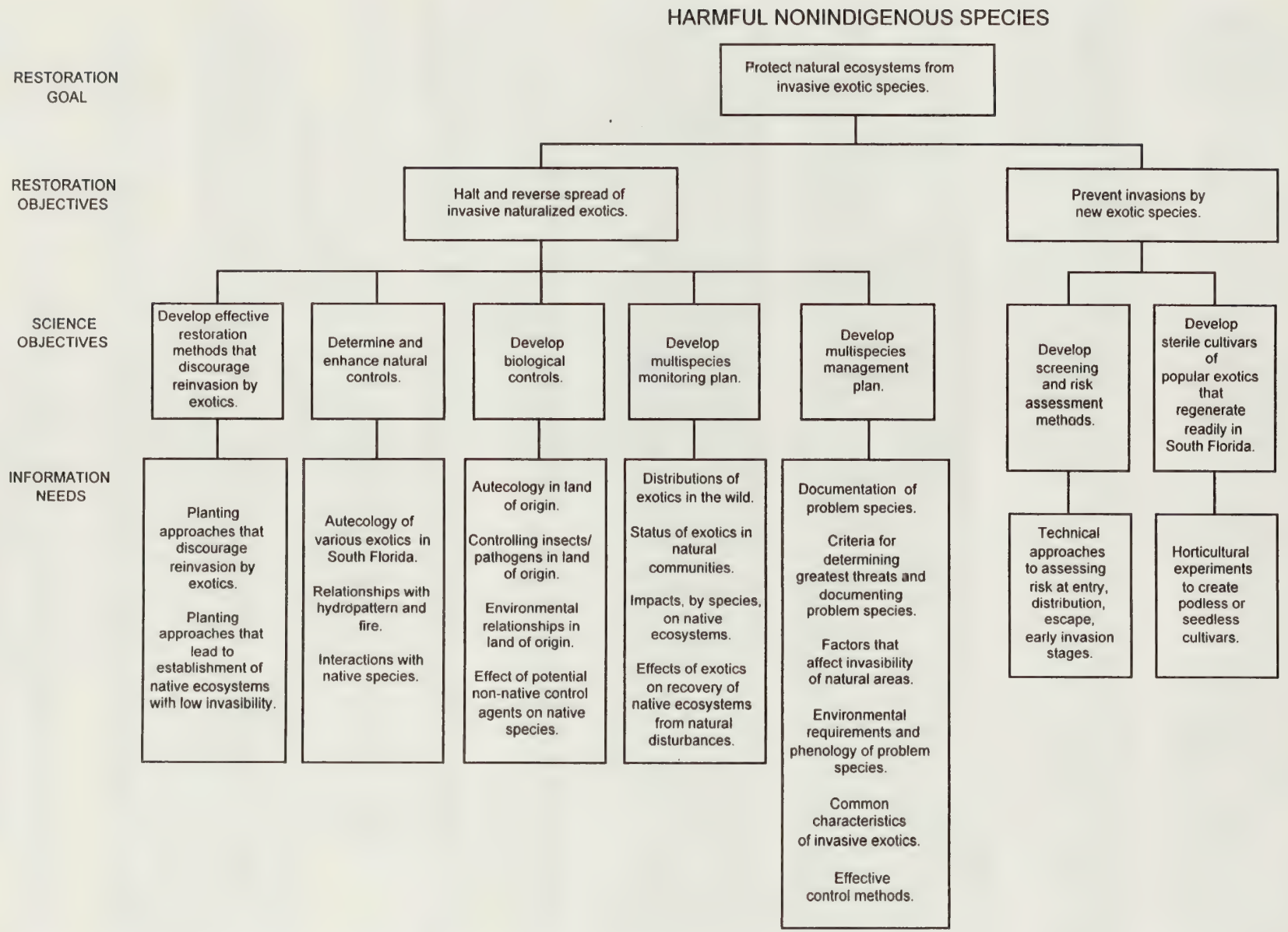

HARMFUL NONINDIGENOUS SPECIES
RESTORATION GOAL
Protect natural ecosystems from invasive exotic species.
RESTORATION OBJECTIVES
Halt and reverse spread of invasive naturalized exotics.
Prevent invasions by new exotic species.
SCIENCE OBJECTIVES
Develop effective restoration methods that discourage reinvasion by exotics.
Determine and enhance natural controls.
Develop biological controls.
Develop multispecies monitoring plan.
Develop multispecies management plan.
Develop screening and risk assessment methods.
Develop sterile cultivars of popular exotics that regenerate readily in South Florida.
INFORMATION NEEDS
Planting approaches that discourage reinvasion by exotics.
Planting approaches that lead to establishment of native ecosystems with low invasibility.
Autecology of various exotics in South Florida.
Relationships with hydropattern and fire.
Interactions with native species.
Autecology in land of origin.
Controlling insects/ pathogens in land of origin.
Environmental relationships in land of origin.
Effect of potential non-native control agents on native species.
Distributions of exotics in the wild.
Status of exotics in natural communities.
Impacts, by species, on native ecosystems.
Effects of exotics on recovery of native ecosystems from natural disturbances.
Documentation of problem species.
Criteria for determining greatest threats and documenting problem species.
Factors that affect invasibility of natural areas.
Environmental requirements and phenology of problem species.
Common characteristics of invasive exotics.
Effective control methods.
Technical approaches to assessing risk at entry, distribution, escape, early invasion stages.
Horticultural experiments to create podless or seedless cultivars.

Figure 4. Goal, objectives, and information needs for efforts on nonindigenous species.

- Common characteristics of invasive non-native species in Florida.
- Effects of nonindigenous plant infestations on native species and the environment.
- Effective habitat restoration strategies to prevent reinvasion by nonindigenous species after their removal.
- Recommendations for implementing integrated pest management strategies.

With respect to nonindigenous animals, scientific study is needed on impacts of these species on food webs, community structure, and populations of species in natural areas in which they have become established. For some taxa, such as insects, even more basic information is needed. Lacking, for instance, is an inventory of insect species (natives as well as known exotics) in South Florida.

► **Develop scientifically based methods for screening and risk assessment to prioritize efforts to control invasions relatively early in the process (importation, distribution, colonization).** (Suggested leads--ARS, NBS, FGFWFC)

Needed are effective criteria to identify and screen potentially invasive or otherwise harmful nonindigenous plants and animals before they become well established here or preferably even before they enter the U.S. Science activities should be integrated with prevention and eradication efforts.

► **Develop a multispecies monitoring plan for nonindigenous plants.** (Suggested Leads--NBS, FWS, NPS)

As part of plan development, existing monitoring programs should be inventoried and analyses made to determine overlaps and gaps in coverage. The plans should ensure that basic variables are defined and measured the same way so that data can be analyzed across areas, not just locally. Activities of the COVER Group should be supported and their efforts incorporated into the plant plan. A computerized atlas of ongoing monitoring programs should be prepared. The FDEP, SFWMD, FLEPPC, and county natural resource agencies should be major partners in plan development.

► **Develop a multispecies monitoring plan for nonindigenous animals.** (Suggested Leads--NBS, FWS, NPS)

Systematic monitoring of probable points of entry of nonindigenous species (Courtenay 1994b) should be a major provision of the animal plan. This is particularly important for fishes, because, once a nonindigenous fish extends its range beyond the point of introduction, eradication becomes impossible and control costs soar to prohibitive levels (Courtenay 1994a). A monitoring program is needed that can detect new introductions early enough for eradication efforts to be made before control is out of the question. The FDEP, FGFWFC, and county natural resource agencies should be major partners in plan development.

► **Prepare a prioritized list of nonindigenous plant species currently and potentially the greatest threats to natural areas. Suggest target areas and species for expanded control efforts.**

Start with the list prepared by the FLEPPC. Use information from the recommended survey and available monitoring results. Develop information on a plant community basis (i.e., pineland, hammock, beach, etc.).

► **Prepare a prioritized list of nonindigenous animal species currently and potentially the greatest threats to natural areas or native plant or animal populations.**

► **Based on information from the above studies, generate brochures and news releases that describe the nonindigenous species problem in South Florida to land managers, decision makers, and the public.**

A public information effort based on scientific information will help develop a greater awareness of the problem and its present and potential impacts on natural areas. Once informed of their contributions to such problems, a concerned public often will change its habits.

► **Conduct horticultural investigations to develop sterile cultivars of popular and widely used, but invasive, non-native ornamental plants, such as certain flowering trees and Ficus species.** (Suggested Lead--USDA)

This technology is being used elsewhere for aesthetic reasons. For instance, fruitless mulberry trees, podless locust trees, and cottonless cottonwood trees are very popular nursery items in the southwestern United States. The Hong Kong orchid tree (*Bauhinia variegata*), a popular ornamental plant in South Florida, is a local example. Species such as royal poinciana, Surinam cherry (*Eugenia uniflora*), the exotic *Scaevola*, and the many ornamental *Ficus* trees would be good candidates for this treatment. Development of sterile cultivars of non-natives with invasive tendencies could provide long-term benefits to natural areas. The FLEPPC list should be used to select non-native trees and shrubs whose propagation outside of cultivation should be controlled.

► **Encourage cultivation and use of native species in landscaping with special promotions to "introduce" promising native species to growers and the public.**

Over 100 tree species alone are native to South Florida, most growing nowhere else in the continental U.S. They are adapted to South Florida's soils and climate, and many are appropriate for landscaping. Greater use of native species in landscaping will reduce the probability of invasions by nonindigenous species.

► **Encourage the expansion into Southeast Florida of commercial operations that produce landscape mulch from melaleuca and other pest plants.**

At least two companies currently produce melaleuca mulch, but they do not appear to be operating on the East Coast of South Florida.

► **Encourage development and use of biological controls in place of pesticides to control pest species.**

Particularly with respect to large-scale, repeated applications, use of biological controls instead of pesticides has enormous potential to reduce damaging environmental impacts often associated with efforts to control exotics in managed areas such as agricultural fields, golf courses, and lawns.

BIBLIOGRAPHY

Bodle, M.J., A.P. Ferriter, and D.D. Thayer. 1994. The biology, distribution, and ecological consequences of *Melaleuca quinquenervia* in the Everglades. Pages 341-355 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Daytona Beach, Florida.

Center, T.D., J.H. Frank, and A. Dray Jr. 1994. The biological control of invasive non-indigenous species in Florida. Pages 209-214 *in* D.C. Schmitz and T.C. Brown, editors. An Assessment of Invasive Non-indigenous Species in Florida's Public Lands. Technical Report No. TSS-94-100. Bureau of Aquatic Plant Management, Division of Environmental Resources Permitting, FDEP, Tallahassee, Florida.

Courtenay, W.R. Jr. 1994a. Non-indigenous fishes in Florida. Pages 57-63 *in* D.C. Schmitz and T.C. Brown, editors. An Assessment of Invasive Non-indigenous Species in Florida's Public Lands. Technical Report No. TSS-94-100. Bureau of Aquatic Plant Management, Division of Environmental Resources Permitting, FDEP, Tallahassee, Florida.

Courtenay, W.R. Jr. 1994b. Current major pathways of fish introductions. Pages 64-66 *in* D.C. Schmitz and T.C. Brown, editors. An Assessment of Invasive Non-indigenous Species in Florida's Public Lands. Technical Report No. TSS-94-100. Bureau of Aquatic Plant Management, Division of Environmental Resources Permitting, FDEP, Tallahassee, Florida.

Doren, R.F., L.D. Whiteaker, G. Molnar, and D. Sylvia. 1990. Restoration of former wetlands within the Hole-in-the-Donut in Everglades National Park. Proceedings of the Seventeenth Annual Conference on Wetlands Restoration and Creation. Hillsborough Community College, Plant City, Florida.

Florida Exotic Pest Plant Council. 1995. Exotic Pest Plant Council's 1995 list of Florida's most invasive species. FLEPPC, West Palm Beach, Florida.

Frank, J.H. 1994. Inoculative biological control of mole crickets. Pages 467-475 *in* A. Leslie, editor. Handbook of Integrated Pest Management for Turf and Ornamentals. CRC Press, Boca Raton, Florida.

Frank, J.H., and E.D. McCoy. 1994. Invasive adventive insects and other organisms in Florida. Introduction to insect behavioral ecology: the good, the bad, and the beautiful: non-indigenous species in Florida. Florida Entomologist 78:1-5.

Frank, J.H., and M.C. Thomas. 1994. *Metamasius callizona* (Chevrolat) (Coleoptera: Curculionidae), an immigrant pest, destroys bromeliads in Florida. The Canadian Entomologist 126:675-682.

LaRoche, F.B., and A.P. Ferriter. 1992. The rate of expansion of melaleuca in South Florida. Journal of Aquatic Plant Management 30:62-65.

Lorenz, J.J. 1993. Influence of hydrology on fish populations in the mangrove dominated zones of the C-111 and Taylor Slough basins and Biscayne Bay. Progress Report to Everglades National Park. NAS, Tavernier, Florida.

McCann, J.A., L.N. Arkin, and J.D. Williams. 1995 Draft. Nonindigenous Aquatic and Selected Terrestrial Species of Florida: Status, Pathway, and Time of Introduction, Present Distribution, and Significant Ecological and Economic Effects. NBS, National Fisheries Research Center, Gainesville, Florida.

Melaleuca Task Force. 1994. The Melaleuca Management Plan for Florida. Recommendations from the MTF. Second Edition, April 1994.

Office of Technology Assessment. 1993. Harmful non-indigenous species in the United States. OTA-F-565. GPO, Washington, D.C.

Robertson, W.B. Jr., and P.C. Frederick. 1994. The faunal chapters: contexts, synthesis, and departures. Pages 709-737 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Schmitz, D.C., and T.C. Brown, editors. 1994. An assessment of invasive non-indigenous species in Florida's public lands. Technical Report No. TSS-94-100. Bureau of Aquatic Plant Management, Division of Environmental Resources Permitting, FDEP, Tallahassee, Florida.

Schmitz, D.C., J.D. Schardt, A.J. Leslie, F.A. Dray Jr., J.A. Osborne, and B.V. Nelson. 1993. The ecological impact and management history of three invasive alien aquatic plant species in Florida. Pages 173-194 *in* B.N. McKnight, editor. Biological Pollution: The Control and Impact of Invasive Exotic Species. Proceedings of a Symposium, October 25 & 26, 1991. Indiana Academy of Science, Indianapolis, Indiana.

Simberloff, D. 1994. Why is Florida being invaded? Pages 7-9 *in* D.C. Schmitz and T.C. Brown, editors. An Assessment of Invasive Non-indigenous Species in Florida's Public Lands. Technical Report No. TSS-94-100. Bureau of Aquatic Plant Management, Division of Environmental Resources Permitting, FDEP, Tallahassee, Florida.

South Florida Ecosystem Restoration Interagency Working Group. 1994. 1994 Annual Report. Available from ENP, Homestead, Florida.

U.S. Army Corps of Engineers. 1995. Environmental assessment for an integrative approach to *Melaleuca* management in the State of Florida. COE, Jacksonville, Florida.

Warren, M.L., and B.M. Burr. 1994. Status of freshwater fishes of the United States: overview of an imperiled fauna. Fisheries (Bethesda) 19(1):6-18.

Woodall, S.L. 1980. Integrated methods for melaleuca control. Pages 135-140 *in* R.K. Geiger, compiler. Proceedings of *Melaleuca* Symposium, September 23-24, 1980. FDACS, FDOF, Tallahassee, Florida.

MERCURY IN THE ECOSYSTEM

INTRODUCTION

Beginning with detection of elevated levels of mercury in largemouth bass in 1989 (FSU 1990; Ware et al. 1990), it has become increasingly apparent that the South Florida Ecosystem is extensively contaminated. In response to continuing accretion of reports of significant Hg contamination, the State of Florida has issued human health advisories that ban or restrict consumption of freshwater fishes from over 2 million acres of the Everglades and Big Cypress Swamp. Although Hg contamination has been detected at levels of concern in largemouth bass throughout the State (Lange et al. 1993), maximum concentrations found in Everglades largemouth bass (4.4 mg/kg) and bowfin (>7 mg/kg) are the highest Hg contaminant levels thus far reported from Florida waters. Mercury accumulation through the food chain may reduce the breeding success of wading birds (Frederick and Spalding 1994) and the viability of the endangered Florida panther (Roelke et al. 1991).

The sources, distribution, and pathways of transport and transformation of Hg through the South Florida Ecosystem are not well understood. Mercury has been sequestered in the oligotrophic circumneutral Everglades peats through the 5,000-year period of their development. Subsidence of these soils following drainage and enhancement of their nutrient status during agricultural conversion may be mobilizing this geochemical reservoir. The natural Everglades soils were not strongly anaerobic, even though flooded for much of the year (Bachoon and Jones 1992), and increasing anaerobiosis may lead to increases in the importance of organic Hg species in Hg biogeochemical cycles. The 1400 miles of canals now in the system, with their low oxygen content, may provide a primary locale for methylation of Hg and its transport through the system in association with dissolved and finely divided organic matter. Potentially significant external sources include atmospheric deposition from the global and regional background and deposition from more local fossil-fuel electric power plants, garbage incinerators, paints, medical laboratories, and fossil residues from Hg-containing agricultural chemicals.

Action to control or correct the problem of Hg contamination of the Everglades biota must await a better understanding of the sources and biogeochemical dynamics of the element. There are seven kinds of policy-relevant questions that must be answered (EPA 1993):

- What is the magnitude of the problem? What are the current levels of Hg contamination in various species? What ecological resources of interest are being adversely affected by Hg?
- What is the extent of the Hg problem? What is the geographic distribution of the problem? Is it habitat specific?
- Is the problem getting worse, getting better, or staying the same?
- What factors are associated with, or contribute to, MeHg accumulation in sensitive resources?
- What are the contributions and importance of Hg from different sources?
- What are the risks to different ecological systems and species from Hg contamination?
- What management alternatives are available to ameliorate or eliminate Hg contamination?

The EPA Region 4 Environmental Services Division is conducting field studies intended to delineate the extent, magnitude, and trends of the Hg problem and to generate data for the initial phase of a formal risk assessment (EPA 1993; Stober et al. 1992). All these activities are part of a larger interagency effort (SFWMD et al. 1994). The habitat types sampled include canals, ponds, sloughs, wet prairies, sawgrass marsh, and hammocks/tree islands. Canal sampling began in September 1993, with other tasks initiated in fall and winter of 1993-94. Water, soil, sediment, and biota are sampled using the EMAP probabilistic design. Regional air monitoring is being conducted by the Florida Atmospheric Mercury Study, supported by Florida Power & Light, Electric Power Research Institute, FDEP, and EPA. The Division is also participating in development of analytical capabilities for measuring Hg at the parts-per-trillion level in water and air.

This chapter describes the high-priority scientific investigations needed to develop the ability to predict the efficacy of policy alternatives. Sections are devoted to microbial methylation and demethylation dynamics, inorganic

chemistry, ecological dynamics, and aquatic and atmospheric modeling. Each section includes discussions of issues, current studies, and information needs. Figure 5 summarizes the information needs relative to restoration and science objectives.

BIOLOGICAL TRANSFORMATIONS

Background

The high levels of MeHg accumulating in fish and other fauna of South Florida may result from either increasing inputs of Hg to the system or changing environmental conditions that promote formation and transport of MeHg. Although some abiotic methylation of Hg may occur, the predominant mechanism for formation of MeHg in the environment is microbial (Berman and Bartha 1986). Thus, increases in concentration of the methyl form of the element indicate either higher available concentrations of inorganic Hg or higher rates of microbial transformation activity, or both.

Although there is little information about distribution and transformations of Hg in wetlands, the problem of elevated Hg in fish has been noted in lakes experiencing point source inputs of Hg, recent impoundments, acid inputs, or combinations thereof (Hakanson et al. 1988; Jackson 1988). Methyl mercury, which constitutes a small fraction of total environmental Hg, is the predominant form of Hg present in contaminated fish (Westõõ 1973) and is bioaccumulated at high rates (Boudou and Ribeyre 1985). Methyl mercury, introduced as a point source into Minamata Bay, was also identified as the compound responsible for the widespread human toxicity associated with consumption of local fish in Minamata, Japan, in the late 1960s (D'Itri 1972).

More commonly, however, environmental Hg contamination cannot be attributed to external sources, but rather stems from alterations of environmental conditions that mobilize Hg and promote uptake via methylation. Widespread Hg contamination was identified in lakes in Scandinavia, eastern Canada and the north-central U.S. (Hakanson et al. 1988, Jackson 1988); surveys of affected lakes implicated acidification of poorly buffered lakes and/or recent impoundment as contributing to elevated Hg levels in fish.

The distribution of total Hg in soils and sediments of Everglades (Delfino et al. 1993) indicates an increase in the accumulation rates of Hg for the 90 years since the turn of the century, with pronounced increases dating from 1940. The similarity of these data to trends in lakes of the north-central U.S. and Sweden, despite differences in climate, hydroperiod, vegetation and location, implicates the worldwide increases in Hg inputs accompanying industrialization. However, the distribution of increases in accumulation rates within the Everglades is not uniform; WCA 1 and WCA 2 have the highest increases, implicating either localized sources or internal transport and transformation processes.

There are no historic or present measurements of Hg methylation in the Everglades; thus no direct comparisons of the rates of methylation between the Everglades and other systems, or between present-day and historic rates within the Everglades, can be made. Rather, present and past conditions in the Everglades can be compared with those factors known to control rates of Hg transformations in other surface water systems to formulate hypotheses about current levels of MeHg and its uptake into the food chain.

The net rate of Hg methylation in the environment reflects the relative rates of two microbial processes: methylation and demethylation. Methylation is primarily carried out by sulfate-reducing bacteria in both freshwater and saltwater systems. Although many bacteria carry out methyl transfer reactions, and thus could potentially methylate Hg, the only identified species to effect these reactions to date have been sulfate-reducing bacteria (Compeau and Bartha 1985; Gilmour et al. 1992). The basis for this apparent specificity has been investigated, but is still not well understood (Choi and Bartha 1993). On the other hand, field experiments in which sulfate-reduction has been inhibited by additions of molybdate have yielded appreciable levels of Hg methylation (Mack and Nelson, unpublished data) suggesting other bacterial groups may also contribute to methylation. Demethylation can occur by two or more pat[illegible]ays (Oremland et al. 1991); the importance of each pathway under different environmental conditions has not been well-characterized, but may result in different net rates of methylation.

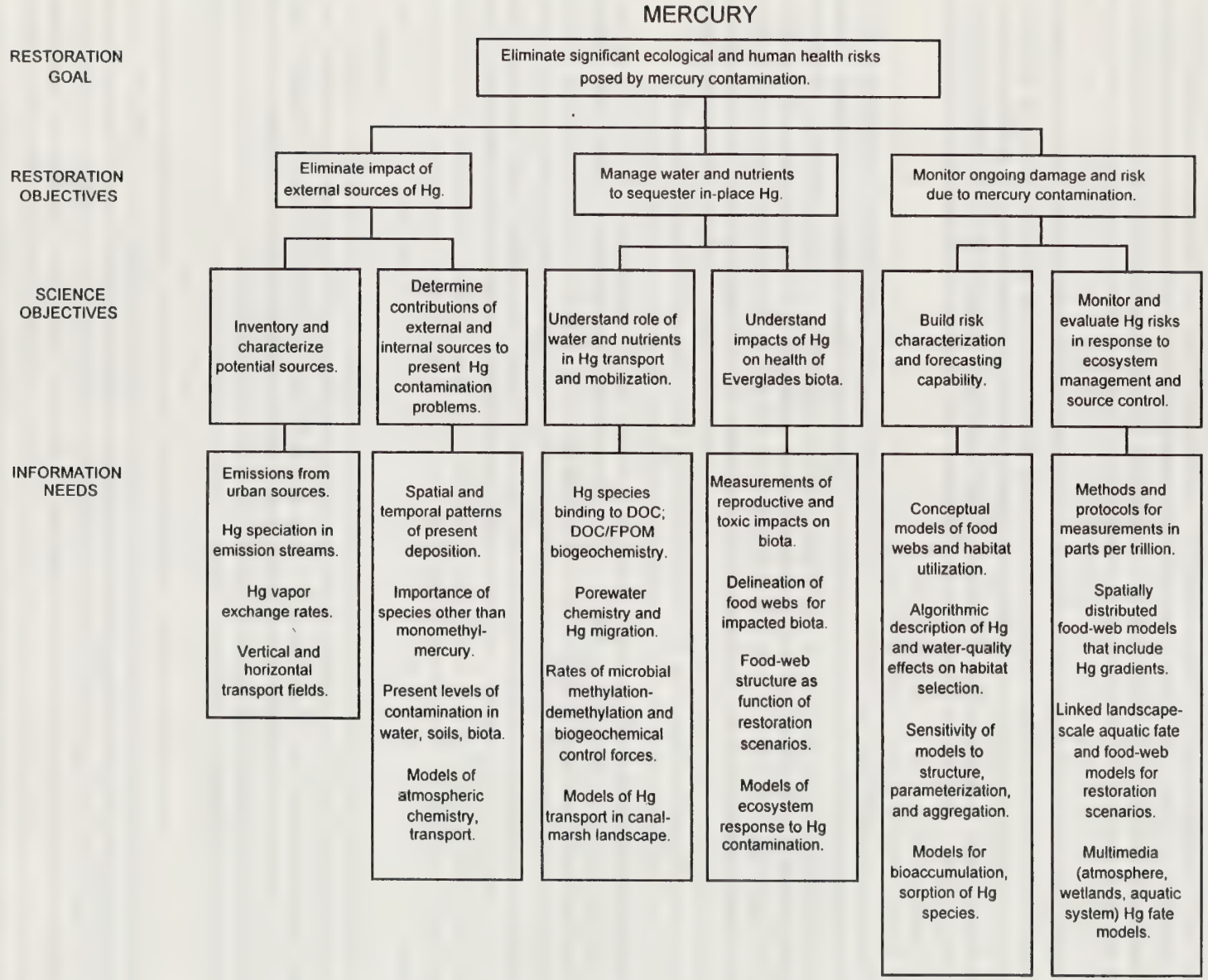

MERCURY
RESTORATION GOAL
Eliminate significant ecological and human health risks posed by mercury contamination.
RESTORATION OBJECTIVES
Eliminate impact of external sources of Hg.
Manage water and nutrients to sequester in-place Hg.
Monitor ongoing damage and risk due to mercury contamination.
SCIENCE OBJECTIVES
Inventory and characterize potential sources.
Determine contributions of external and internal sources to present Hg contamination problems.
Understand role of water and nutrients in Hg transport and mobilization.
Understand impacts of Hg on health of Everglades biota.
Build risk characterization and forecasting capability.
Monitor and evaluate Hg risks in response to ecosystem management and source control.
INFORMATION NEEDS
Emissions from urban sources.
Hg speciation in emission streams.
Hg vapor exchange rates.
Vertical and horizontal transport fields.
Spatial and temporal patterns of present deposition.
Importance of species other than monomethyl-mercury.
Present levels of contamination in water, soils, biota.
Models of atmospheric chemistry, transport.
Hg species binding to DOC; DOC/FPOM biogeochemistry.
Porewater chemistry and Hg migration.
Rates of microbial methylation-demethylation and biogeochemical control forces.
Models of Hg transport in canal-marsh landscape.
Measurements of reproductive and toxic impacts on biota.
Delineation of food webs for impacted biota.
Food-web structure as function of restoration scenarios.
Models of ecosystem response to Hg contamination.
Conceptual models of food webs and habitat utilization.
Algorithmic description of Hg and water-quality effects on habitat selection.
Sensitivity of models to structure, parameterization, and aggregation.
Models for bioaccumulation, sorption of Hg species.
Methods and protocols for measurements in parts per trillion.
Spatially distributed food-web models that include Hg gradients.
Linked landscape-scale aquatic fate and food-web models for restoration scenarios.
Multimedia (atmosphere, wetlands, aquatic system) Hg fate models.

Figure 5. Goal, objectives, and information needs for efforts on mercury.

Sulfate concentrations below 1 μM in freshwater systems inhibit the rate of methylation (Gilmour et al. 1992). The increases in Hg methylation observed in acidified temperate lakes can be attributed to sulfate fertilization rather than to direct pH effects. The high levels of sulfate in marine systems also inhibit methylation (Winfrey and Rudd 1990) by promoting precipitation of Hg as sulfides. The concentrations of sulfate in the waters of the Everglade (5-170 mg/L; Stober et al. 1995) span the 20-40 mg/L concentration range thought to be optimal for Hg methylation (Gilmour and Henry 1991). Thus, although sulfate concentrations in the Everglades have probably not changed appreciably (the high concentrations relative to other fresh waters are due to underlying mineralogy rather than acid rain inputs), the high levels of sulfates may predispose the system to respond strongly to removal of other limitations on methylation.

Other factors that may influence the rate of methylation include temperature, pH, DOC, and aeration status (Compeau and Bartha 1984; Miskimmin et al. 1992; Winfrey and Rudd 1990). Seasonal studies of microbial transformations of Hg indicate higher rates of methylation in summer than in winter (Bodaly et al. 1993; Korthals and Winfrey 1987). Given that most studies of microbial methylation have occurred in mid- to high-latitude lakes, the higher temperatures of the Everglades suggest potential rates of methylation in this system are unlikely to be limited by temperature as they are in temperate systems.

The aeration status of areas in South Florida may have changed in response to changes in hydrology and oxygen demand, as mediated by loadings of inorganic nutrients. Drainage of peat soils causes oxidation of organic matter from the soils, especially when microbial respiratory activity is enhanced by nutrient additions. The fate of any Hg associated with such soil loss in the Everglades is not known. Canalization and eutrophication may also have increased the extent of anaerobic zones within the water column, giving rise to areas of potentially high methylation activity. Additionally, eutrophication may increase activity of sediment microbial populations, making the sediments more strongly anaerobic. Such conditions favor activity of the sulfate-reducing bacteria responsible for methylation of Hg. Thus, eutrophication may affect the rate of methylation by both direct and indirect mechanisms.

Alteration of hydrology and nutrient status may also change the nature and composition of the organic matter cycled and transported within the system. In oligotrophic wetlands, much organic carbon is tied up as lignocellulose, or plant detrital material, which cycles slowly. Under more eutrophic conditions, algal growth and higher microbial activity increase the lability of the carbon. Increases in organic matter generally support higher microbial activity but may also complex the Hg, decreasing its availability for methylation. It is difficult, therefore, to predict the direction of change that may result from changes in character, amount, and distribution of organic matter.

Major Issues

An understanding of Hg transformation processes is critical to discerning and mitigating the sources of Hg in the system and reducing ecological exposures. Mercury species vary greatly in their physical properties, such as volatility, solubility, partitioning, as well as their bioavailability. Are the high levels of MeHg in fish and animals in the Everglades due to inputs of Hg or to internal transport and transformation? Examination of available data and consideration of hydrological and land-use changes that have occurred suggest that either or both phenomena may contribute to the current levels of contamination.

Existing Hg models represent microbial transformations of Hg as a single, first-order process resulting in the net production, or destruction, of MeHg (PTI 1994). Such models have been shown to be sensitive to the microbial transformation rate and to exchanges between benthic and water column compartments. Two major issues confound the useful representation of microbial processes in the models: 1) the inherent variability of experimental determinations of transformation rates (Gilmour and Henry 1991; PTI 1994) and 2) the lack of mechanistic understanding of the transformation processes. The latter is especially critical if models are to be used as insights into historical alterations of the Everglades system that may have contributed to mobilization and internal transport of Hg and as tools for predicting outcomes of mitigation scenarios.

Current Studies

Region 4 of the EPA is conducting a research program with the support of other Federal and State agencies. This program, R-EMAP, uses a probabilistic sampling strategy to determine distribution of MeHg and total Hg in water, sediments, and fish, as well as pertinent environmental parameters (e.g., temperature, DO, nutrient and sulfate concentrations, alkaline phosphatase activity, conventional soil parameters). Sampling efforts have been designed to support the testing of specific hypotheses for the distribution and transport of Hg; e.g., sampling efforts have followed longitudinal transects in canals and across nutrient (especially phosphorus) gradients. Present information indicates that the region of highest Hg concentration extends from WCA 3A south into the Shark Slough area of ENP. The zone within WCA 3 near the L-67 and Miami canals has the highest reported Hg concentrations for several species, including great white heron, mosquitofish, largemouth bass, and bowfin (COE 1995).

A preliminary laboratory investigation was supported by EPA to determine the effect of nutrient additions on methylation rates in microcosms (Kavanaugh and Barkay 1992). Methylation and demethylation were shown to be stimulated by additions of phosphorus to Everglades soils.

A field study jointly funded by the SFWMD, USGS, and FDEP was conducted between January 1992 and February 1993 to determine historical baseline concentrations of Hg in Everglades and Okefenokee sediments, post-industrial changes in sediment Hg accumulation, and spatial distribution of Hg throughout the Everglades (Delfino et al. 1993). This study found that average Hg concentrations in the surface sediments (n=51) was 121 ng/g and surface concentrations averaged 2.5 times higher than concentrations deeper in the profile. Extractable organic Hg averaged 52% (range 6-100%) of total; this fraction probably includes both MeHg and additional Hg species. Mercury accumulation rates started to increase ca. 1940, coincident with the mid-century alteration of hydrology and agricultural and urban development of South Florida.

A study plan has been developed to address concerns about Hg transformations and mobilization that might accompany the Everglades Nutrient Removal Project and the STAs proposed for cleansing agricultural runoff (SFWMD et al. 1994). Although the ENR is designed primarily to remove phosphorus, it also presents an excellent opportunity to test hypotheses regarding Hg transformations, especially those pertaining to effects of eutrophication and alteration of aeration status. In addition to manipulations planned for the ENR as a whole, microcosms and sediment material derived from the area will be suitable for testing responses to different concentrations of phosphorus or other experimental treatments. The ENR has been designed to mimic the hydrology of WCA 2A; no additional manipulations (physical, chemical or biological) are planned for enhanced removal of nutrients. It is projected that long-term nutrient removal will occur as a consequence of peat accumulation under anaerobic conditions; it is not known whether Hg will be sequestered or released under those conditions (Sugar Cane Growers Cooperative 1994).

As part of EPA and FDEP permitting requirements, total recoverable Hg and MeHg will be monitored at the inflow and outflow of the ENR site, as well as at a location upstream of the outflow in the L-7 Borrow Canal. Requirements of the permit also stipulate that body burdens in fish and shellfish be monitored for 2 years of operation. Fluxes of total, particulate, and dissolved Hg will be measured to determine the mass balance of Hg species, as will rates of Hg accumulation in sediments. An atmospheric Hg monitoring station, operated by the Florida Atmospheric Monitoring Study, has been constructed to measure atmospheric fluxes to the site.

The SFWMD (1993) has also proposed studies under the Section 319 Non-point Sources Grants Program to determine the effects of Best Management Practices implemented in the EAA on Hg loadings to the Everglades. Three categories of practices will be evaluated: 1) traditional on-farm changes in water and fertilizer application practices, 2) buffer strips or retention ponds, and 3) a large-scale constructed wetland to be managed by a consortium of farmers.

The USGS has been investigating the interactions between hydrological and chemical processes and distribution of MeHg, focusing on the speciation and complexation of Hg. It also is investigating the controls on methylation processes by manipulating sediment cores from canal and marsh locations within the Everglades. This effort is being coordinated with other Federally funded projects and includes co-location of sampling with R-EMAP sites.

In addition to the R-EMAP sampling effort supported by EPA Region 4, EPA plans to support basic investigation into the mechanisms that control net rate of Hg methylation with the goal of developing models for the kinetics of the process. Two projects have been funded. One will investigate the response of demethylation processes to environmental factors and the resultant effect on net methylation rates, along with the role of methylating agents. The second will investigate the environmental processes that control the rate of methylation. Efforts will be made to determine methylation/demethylation rates in materials derived from R-EMAP sampling sites. Results of these experimental investigations will be incorporated into development of biogeochemical models that link microbial transformations of Hg with carbon, sulfur, and nutrient cycling.

The proposed integrated program also includes creation of a GIS database for environmental parameters that may control transport and transformation of Hg in South Florida (e.g., soil types; vegetation; hydrology; agricultural crops; wildlife distribution; fertilizer and pesticide applications; nutrient concentrations; water chemistry; and Hg concentrations in soils, sediments, and water).

Information Needs

Critical Questions

Given the role of MeHg in uptake and accumulation of Hg by biota, an understanding of the formation and fate of this compound is essential for development of risk assessments and ameliorative strategies. Such an understanding must be based on a science program that addresses the following questions:

- What are the environmental factors that influence rates of microbial methylation and demethylation? How are these factors constrained by present conditions and historical changes in hydrology and land use of the Everglades? Changes in nutrients, oxygen, and organic carbon must be considered.

- How do organic matter and alterations of organic matter that may result from changing nutrient and oxygen status affect availability of Hg for microbial transformations and the activity and composition of microbial populations that carry out the Hg transformations?

- How do ecological zones and/or land uses influence rates of methylation and demethylation? Can characterization of such zones be used to construct a mass balance and transport model for Hg in the Everglades?

- What is the impact of alterations of aeration status, such as that resulting from periodic inundation and dewatering of agricultural lands, on release and transformation of Hg?

- Do forms of organomercury other than MeHg occur in waters and sediments of the Everglades? If so, what are the implications of other organomercury forms for transformation pathways and bioaccumulation?

- Do demethylation processes differ under different aeration regimes and in different ecological zones? What is the impact of oxidative versus reductive demethylation pathways on the net rate of methylation?

A science program that addresses these questions will support construction of a biogeochemical model that integrates methylation of Hg with carbon, nitrogen, phosphorus, and sulfur cycles. Such a model will link microbial activity with environmental parameters to test explanatory hypotheses for fate and transport of Hg and predict the consequences of mitigation strategies.

Approach

Two complementary approaches are essential to resolve questions on the sources and fate of Hg within the Everglades: 1) determination of distributions, and 2) experimental investigations of transport and transformation processes. Both efforts are critical for distinguishing among the hypotheses proposed to explain the high concentrations of MeHg in biota. Recent and ongoing research focuses on determining the extent of Hg contamination; current distribution of Hg species in sediment, water and fish; and historical distribution of total Hg in sediments.

Models for the rates of Hg transformations, as derived from the process-based investigations, must be tested and implemented based on specific geographic data. Initially, a mass-balance approach could be used to estimate Hg transformations associated with large-scale land use and ecological zones. Subsequent efforts would implement Hg transformation models within the Hg cycling and transport models.

Also needed is appropriate characterization of ecological zones and land uses, both present-day and historical, in the Everglades with respect to conditions that influence rates of M/D, in order to integrate and analyze data on the forms and concentrations of Hg.

Specific needs not directly addressed in current or proposed research plans include:

- Origin of the organic matter (e.g., periphyton vs. detritus of emergent plants) that serves as the microbial substrate for methylation, as it is impacted by altered nutrient and aeration conditions.

- Effects of periodic inundation of agricultural lands.

- Importance of organomercury species other than MeHg.

ABIOTIC BIOGEOCHEMICAL AND TRANSPORT PROCESSES

Background

Mercury occurs in the environment as a number of species, which display species-dependent partitioning, bioavailability, rates of interconversion, and overall fate and transport. This section outlines ongoing and future research on those aspects of environmental inorganic Hg speciation that must be understood to assess Hg bioavailability in South Florida.

Of the various environmental species of Hg discussed in the scientific literature, monomethylmercury (CH_3Hg^+) is the dominant species associated with bioavailability and biomagnification (Driscoll et al. 1994; Zillioux et al. 1993). Monomethylmercury typically represents ca. <1%-10% of the total Hg in a given water sample. Divalent Hg (Hg^{2+}) is the most thermodynamically stable species in oxic environments; it also may represent the dominant form of Hg in the water column and the dominant atmospheric species deposited either through dry or wet deposition. Elemental Hg (Hg^o) is presumably formed primarily through microbial reduction and, because of its high vapor pressure (Lindquist and Rohde 1985), may be the most significant volatile species lost to (and present in) the atmosphere. Dimethyl mercury ($(CH_3)_2Hg$) is another volatile species (Lindquist and Rohde 1985) that presumably can be formed in sediments, albeit at rates 6,000 times less than that of monomethylmercury (Wood 1974).

There is ample scientific evidence that many of the environmental Hg species are intimately associated with natural organic carbon (Alberts et al. 1974; Andren and Harriss 1973, 1975; Billen and Wollast 1973; Driscoll et al. 1994; Gill and Bruland 1990; Hurley et al. 1994; Lindberg and Harriss 1974; Robertson et al. 1987; Xu and Allard 1991; Zillioux et al. 1993). Unfortunately, a fundamental (mechanistic) understanding of Hg partitioning with natural organic carbon is not currently available. Without this understanding, a reliable analysis of the probable effect of restoration and management actions on Hg dynamics cannot be accomplished.

Major Issues

Although recreational use of the Everglades and other South Florida areas has been impaired by fish advisories, observed Hg concentrations in soils/sediments do not appear to be present at exceptionally high concentrations (Cantillo et al. 1993; Delfino et al. 1993; Long and Morgan 1990). Also, assuming monomethylmercury (CH_3Hg^+) is the dominant bioavailable species and South Florida is comparable to other environs, Hg methylation is likely to be most significant in surficial sediments (Billen and Wollast 1973; Callister and Winfrey 1986; Jernelov 1970).

The major issue is: What is the source of the Hg in the surficial sediments that becomes available for methylation? Is it Hg ultimately derived from external sources that is freshly deposited in the sediments? Or is it Hg migrating from deeper strata within the sediments? Answering these questions requires a technical capability for assessing Hg migration in sediments, which in turn requires the ability to assess porewater Hg concentration gradients established by background sedimentary biogeochemical processes. Technical projects designed to assist in answering the above questions focus on employing recent scientific advances in the understanding of sedimentary processes and speciation-dependent binding with organic carbon.

The two issues to be addressed in the near term are: 1) development of region-specific process models to describe Hg species-dependent binding with naturally occurring organic matter and 2) development of region-specific methods to assess Hg migration in sediments.

Current Studies

Current investigations on the abiotic processes relevant to Hg speciation are being conducted primarily via an Interagency Agreement between the EPA and USGS. These efforts include developing an experimental dataset of Hg binding with natural organic carbon (obtained from the South Florida Region), developing fundamental process-based models of observed Hg species-dependent binding behavior, and investigating the potential migratory behavior of Hg in sediments from the South Florida Ecosystem. This last aspect builds (in part) on application of a steady-state sediment model produced under an existing cooperative agreement between EPA's Environmental Research Laboratory-Athens and the Georgia Institute of Technology (A General Transport Reaction Model for Freshwater Sediments; Van Cappellen and Wang, in press).

Information Needs

Critical questions

▸ Divalent and monomethylmercury are known to exhibit substantial binding with natural organic carbon under most oxic environmental conditions. Although this binding is significant to environmental fate, methylation, and ultimate bioavailability, the mechanistic processes involved are not well understood. Are the binding properties of natural organic carbon in South Florida commensurate with the properties of organic carbon found elsewhere? Does ionic Hg in South Florida bind with natural organic carbon in a manner comparable to binding observed elsewhere? What quantitative predictive relationships can be developed to assess Hg binding with natural organic carbon?

▸ Elevated total Hg concentrations have been observed in surface sediments in South Florida (Delfino et al. 1993). Are these elevated sedimentary Hg contents the primary source of monomethylmercury to the biosphere or do these elevated surface concentrations merely co-vary with elevated external loadings? Is there a depth in the sedimentary column where Hg becomes relatively non-bioavailable? Will Hg in these sediments experience ecologically significant post-depositional migration?

Approach

Findings obtained from the current research will be applicable as general, process-based methods for assessing environmental Hg speciation and potential sedimentary migration. Because these findings will be the products of more basic investigation, future applications will involve extrapolating relationships derived from carefully controlled laboratory systems to ecological environments (within a framework of statistical uncertainty).

ECOLOGICAL EXPOSURE AND EFFECTS

Background

Mercury contamination in aquatic communities of South Florida is a well documented problem and may be an important contributing factor to the decline of wading bird populations and other top predators, such as the

Florida panther, that are dependent on these contaminated food webs. If the restoration of the South Florida Ecosystem is to be realized fully, decision makers must be able to predict and assess the ecological risk posed by Hg in conjunction with other restoration objectives.

Two basic approaches have been used to quantify the bioaccumulation of environmental pollutants in aquatic and terrestrial biota. The first of these assumes that organisms quickly achieve a chemical equilibrium with respect to a particular media or route of exposure. For aquatic biota, this reference media is generally considered to be the water. For terrestrial plants, on the other hand, the reference media may be the soil or possibly air. For terrestrial animals, the reference media may be either the soil or, more commonly, the animal's principal food items. This approach uses bioconcentration or bioaccumulation factors (BCFs or BAFs) to estimate chemical residues in biota from measured concentrations in the appropriate reference media. BCFs for a variety of mercuric compounds in diverse biota have been reported to vary between $10^{2.4}$ and $10^{6.7}$. Because bioaccumulation/elimination half-lives of most mercuric compounds are extremely long, however, many of the BCFs reported to be less than 10^4 do not represent true equilibrium values. For example, half-lives of MeHg in most vertebrates vary from months to years. Moreover, these half-lives generally will depend on body size and environmental variables such as temperature. The second approach to predict chemical bioaccumulation assumes that chemical exchange is a slow process and that the organism's body burden is not necessarily in equilibrium with any particular exposure media. This approach, which appears to be more appropriate for Hg, predicts bioaccumulation using mathematical models that explicitly simulate the chemical's uptake, metabolism, excretion, and biodilution as a function of the organism's environmental exposures.

Many scientists have studied the bioaccumulation of Hg in diverse biota under natural field conditions. In many cases, these studies have demonstrated a strong correlation between the organism's body size and its body burden of Hg. This trend, which is particularly evident in fish, mollusks, and aquatic mammals is influenced by several factors. Increasing body size, for example, is generally associated with increasing longevity and hence increased temporal exposure; this is a consideration that is extremely important for slowly accumulating chemicals. Increasing body size also increases an animal's exposure to Hg along spatial dimensions. Territory size and home ranges of many vertebrates, for example, are positively correlated with their body size. Given two animals with different sizes of foraging ranges, it is natural to expect the animal with the larger range would be much more likely to encounter contaminated prey than the other. Allometric relationships between body size and feeding also influence this general trend. The simple fact that large animals consume more prey than do small animals obviously increases their exposure probabilities, as does size-dependent home ranges or territories. Another factor contributing to this bioaccumulation trend is that as many predators grow they generally tend to consume larger prey. This trend is particularly evident in predatory fish but is also demonstrated by other predators including snakes and birds. If the Hg concentration in a predator's prey displays a positive correlation with the prey's body size, predators that exhibit size-dependent foraging will be subject to ever-increasing Hg exposures.

These kinetic and allometric considerations strongly suggest that realistic analysis and characterization of Hg contamination in South Florida must be performed using dynamic, process-based bioaccumulation models. This conclusion is also supported by the fact that several authors have shown that total body burdens of Hg in fish and other aquatic biota are often correlated with environmental variables not accounted for by BCF/BAF approaches. For example, Hg burdens are often negatively correlated with water pH and DOC. Whereas the negative correlation between body burden and ambient pH is generally attributed to reduced methylation of Hg under alkaline conditions, the negative correlation between body burden and ambient DOC is generally believed to result from reduced bioavailability of Hg as it binds to sulfhydryl groups of organic molecules. Significant positive and negative correlations between total body burden of Hg in fish and lake size also have been reported. Positive correlations may be explained by the simple fact that large lakes are generally situated in larger watersheds than are small lakes. If atmospheric deposition is the area's most significant Hg source, large lakes would be expected to have higher Hg concentrations than small lakes. The same logic would also hold for large vs. small water impoundments overlying potential sedimentary sources of Hg. Negative correlations, on the other hand, may be explained by the trend of small lakes to have higher average temperatures than large lakes and the positive correlation between rates of MeHg production and temperature (Bodaly et al. 1993).

The ability to accurately predict Hg bioaccumulation is needed to define realistic dietary exposures to wildlife, assess the potential for significant biotic transport of Hg, and predict the onset of residue-based effects that

result from chronic or varying temporal/spatial exposures. Most models of MeHg are very sensitive to changes in elimination rate (Norstrom et al. 1976; Rodgers 1994). There are, however, few rigorous studies of MeHg elimination in fish and no detailed studies of MeHg elimination in fish since the 1980s. The Norstrom equation describing MeHg elimination assumes it is independent of metabolic rate, but MeHg elimination in rainbow trout was significantly affected by meal size and presumably metabolic rate (Rodgers and Beamish 1982). If metabolic rate significantly affects MeHg elimination in fish, the effects would be most pronounced in small prey fish at South Florida temperatures. Similarly, the value used for assimilation of dietary MeHg (reported values range from $<20\%$ - $>80\%$) will significantly affect MeHg bioaccumulation (Norstrom et al. 1976; Rodgers 1994). Accordingly, detailed laboratory and field studies of uptake and elimination of MeHg in representative South Florida species of predatory and prey fish and selected invertebrates under Florida environmental conditions should be undertaken. Results of these studies would then be incorporated into models of MeHg bioaccumulation.

Major Issues

Most ecotoxicological studies of Hg have focused on determination of traditional exposure-based endpoints such as LC_{50}s. These data can differ by two or three orders of magnitude depending on the organisms or life stages considered. Such variations, however, are not surprising since any factor that influences rate of Hg accumulation within an organism should be expected to affect its observed LC_{50}s. Thus, for example, factors that affect respiration of aquatic biota, and hence their gill exchange, should also affect the LC_{50}s of those organisms. Thus, it is not surprising that the LC_{50}s for most aquatic biota are generally decreasing functions of body size, temperature, and duration of exposure. For marine biota, LC_{50}s also depend on salinity.

Although most ecological risk assessments for environmental contaminants traditionally have been founded on exposure-based endpoints such as LC_{50}s and EC_{50}s, effects of chemicals on organisms are not caused by the chemical in the environment but rather by the chemical that is accumulated within the organism. Exposure-based toxicity endpoints have many inherent limitations. Generally these endpoints address only a single route of exposure under constant exposure conditions. For example, acute hazard assessments for fish usually are based on 96-hr LC_{50}s for constant water concentrations. Under field conditions, however, fish will accumulate chemicals not only from the water but also from their prey that also become contaminated. If dietary exposures are more significant than direct aqueous exposures, there is no *a priori* reason to assume hazard assessments based on LC_{50}s would be protective of field populations. Even if both dietary and aqueous toxicity benchmarks are known, there are no rules-of-thumb to determine which toxicity benchmark should be used for all fish or all field exposure scenarios, since the relative significance of various routes of uptake depends on the exposure scenario being considered.

The only objective way to address the consequences of Hg exposure to South Florida biota -- and hence to reduce uncertainties associated with ecological risk assessments of Hg -- is to deal directly with the kinetics of chemical bioaccumulation in organisms and establish appropriate residue-based endpoints.

Current Studies

Several conceptual models describing food webs and habitat utilization in the South Florida Ecosystem have already been developed (see Davis and Ogden 1994). These models document the principal ecological interactions and forcing functions needed to sustain viable populations of the major wildlife species. While most vertebrate wildlife are treated as individual species, invertebrate wildlife are typically treated as functional groups. Several studies have focused on exposure of individual species or ecological guilds to Hg. Wood et al. (1993) used blood and feather samples and carcasses to assess Hg exposures in bald eagles; Sundlof et al. (1994) summarized data for exposure in wading birds. Jurczyk (1993) constructed a preliminary ecological risk assessment for species including the Florida panther and American alligator. Summaries of ecological exposures to South Florida biota are available as abstracts presented at the international meeting, "Mercury as a Global Pollutant (1994)".

The NBS and NPS are currently developing, via the ATLSS program, physiologically based models for several key species of Everglades wildlife, including the American alligator, wood stork, white ibis, snail kite, Cape Sable seaside sparrow, Florida panther, and white-tailed deer. ATLSS considers the impacts of habitat and contaminant stresses (including Hg and other compounds) as mediated by trophic transfers. EPA's Ecosystems Research Division in Athens, Georgia, has begun modification of the FGETS (Food and Gill Exchange of Toxic

Substances) bioaccumulation model to analyze bioaccumulation of Hg in Everglades fish communities. FGETS is a process-based model that describes the bioenergetics and bioaccumulation of organic chemicals of arbitrarily specified age-structured fish assemblages.

Habitat suitability models for vertebrate wildlife species will be reviewed and used as an integral part of this research. These models should be used as the initial, but not necessarily final, frameworks to address the foraging, nesting/reproductive, and roosting habitat requirements of vertebrate wildlife species of concern. A realistic forest stand model (e.g., FORET, FOREST, JABOWA, KIAMBRAM, SILVA, SWAMP) will be integrated with a wetland foodweb model in order to simulate the structural characteristics of wetland vegetation required by wetland vertebrates for food, shelter, and reproduction. This stand model should be responsive to hydrologic alterations, fire, local and regional climatic factors, and episodic disturbances such was hurricanes.

Information Needs

Critical questions

Over the last 20 years, considerable attention has been focused on monitoring and investigating the bioaccumulation and ecological effects of Hg. Although several review papers have been published on various aspects of ecological exposure and effects of Hg (Depledge and Rainbow 1990; Driscoll et al. 1994; Eisler 1987; Gavis and Ferguson 1972; Jonnalagadda and Prasada Rao 1993; Richman et al. 1988; Sorensen 1991; Zalups and Lash 1994; Zillioux et al. 1993), many aspects of these topics remain unknown or unsynthesized. Major questions regarding Hg bioaccumulation include:

- What is the partitioning and binding behavior of different Hg species within organisms?
- Is the heterogeneous distribution of Hg among tissues a kinetic or equilibrium phenomenon?
- How should Hg bioconcentration in plants be modeled to describe trophic exposures to herbivorous wildlife?
- How do prey availability, size-dependent home ranges, and ontogenetic changes in prey preferences influence bioaccumulation of Hg in aquatic and terrestrial wildlife?
- How does the spatial and temporal distribution of habitat influence bioaccumulation of Hg in highly mobile and migratory wildlife?
- What metabolic transformations of Hg occur that affect its uptake, internal distribution, or excretion?
- Can Hg bioaccumulation be modeled with sufficient accuracy without modeling the concurrent bioaccumulation of other metals that compete for the same sulfhydryl binding sites?
- What water quality parameters (including temperature) influence bioaccumulation of Hg in Everglades aquatic communities? What fate and transport models can be used to simulate these variables?

Major questions regarding ecological effects of Hg include:

- What bioconcentration or bioaccumulation models are available to estimate residue-based toxicity endpoints from previously published exposure-based endpoints?
- What residue levels affect feeding, growth, reproduction, and mortality of South Florida wildlife? What indicator species should be selected for study?
- How should the accumulative effects of multiple mercuric species be quantified? How should the accumulative effects of Hg, other metals, and organics be quantified?

▸ What factors ameliorate Hg toxicity (e.g., selenium species)? How should these factors be incorporated into the Hg modeling program?

Approach

To estimate accurately the ecological effects of Hg in the South Florida Ecosystem, a suite of process-based models supported by user interfaces and databases must be developed to describe the:

▸ nominal trophic dynamics and habitat utilization of vertebrate and invertebrate wildlife in wetland and estuarine ecosystems,

▸ effects of hydrology, water quality, and vegetative habitat structure alterations on these ecological processes,

▸ bioaccumulation of Hg and other persistent organic chemicals and metals in wetland and estuarine biota, including interactions between contaminants, and

▸ direct and indirect effects of chemical contamination on structure and function of wetland and estuarine ecosystems.

Conceptual models describing food webs and habitat utilization in the South Florida Ecosystem should be documented to delineate the principal ecological interactions and forcing functions needed to sustain viable populations of the major wildlife species. While most vertebrate wildlife should be treated as individual species, invertebrate wildlife could be treated as functional groups. Aquatic and terrestrial flora should be characterized at a scale of resolution appropriate to describing the trophic and habitat dependencies of these wildlife components.

Physiologically based models being developed for South Florida wildlife (see above) already address some of the above needs and should be continue to be supported. EPA/ERD-Athens will be modifying the FGETS bioaccumulation model to analyze bioaccumulation and effects of Hg in the South Florida Ecosystem. Because of its generalized structure, other wildlife components can be readily incorporated into the existing FGETS foodweb structure.

Habitat suitability models for vertebrate wildlife species will be reviewed and used as an integral part of this research. These models should be used as the initial, but not necessarily final, frameworks to address the foraging, nesting/reproductive, and roosting habitat requirements of vertebrate wildlife species of concern. A realistic forest stand model (e.g., FORET, FOREST, JABOWA, KIAMBRAM, SILVA, SWAMP) will be integrated with a wetland foodweb model in order to simulate the structural characteristics of wetland vegetation required by wetland vertebrates for food, shelter, and reproduction. This stand model should be responsive to hydrologic alterations, fire, local and regional climatic factors, and episodic disturbances such as hurricanes.

Wetland and estuarine community models should be validated piece-wise using literature data and field and laboratory studies planned as part of the South Florida Ecosystem Restoration. As various submodels are validated, databases of ecological, morphologic., and physiological parameters required by the submodels will be compiled to facilitate rapid and effective model parameterization. User interfaces also will be developed.

AQUATIC MERCURY FATE MODELING

Background

Conceptual models and process submodels of the biogeochemical cycling of Hg, properly distilled, provide a powerful basis for operational site-specific models. Such Hg fate models may be constructed *de novo* or may be built upon the framework of existing chemical transport and fate models. Several existing chemical models treat environmental transport and chemical transformation processes in a general manner that can be used for many organic and inorganic chemicals. These models can be modified to handle the special transfer and transformation

reactions that affect mobility and speciation of Hg. This section discusses development and application of a Hg fate model to specific locations in the Everglades.

Several modeling approaches for describing fate of Hg in watersheds have been undertaken. Recent modeling efforts have usually been based on several simplifications. Some are simplistic in their representation of Hg chemistry. Others, although able to represent some of the complex Hg chemistry, can represent only simple physical environments. Currently, a general modeling framework for the mechanistic simulation of transport and fate of Hg in complex aquatic environments does not exist.

The Mercury Cycling Model mechanistically simulates transport and transformations of Hg in natural lakes (Hudson et al. 1990, 1994). Four Hg components are simulated: Hg(0), Hg(II), MeHg, and Hg(inert). Kinetic transformation reactions are linear with respect to the Hg components but may be modified by other water quality variables. The model handles aqueous complexation using compartment-specific parameters and equilibrium constants. A simple food-chain model is included with direct transfers of Hg through a linear four-step food chain composed of phytoplankton, zooplankton, planktivorous fish, and piscivorous fish. MCM is spatially simple, calculating Hg fate and bioaccumulation in three compartments (epilimnion, hypolimnion, benthic sediment).

MERC4 (Martin 1992) is based on a generalized compartmental modeling system that allows complex physical representation of water bodies with up to 500 segments that can be linked with hydrodynamic models (Ambrose et al. 1987). MERC4 Hg components and reactions were set to emulate MCM; Hg(0), Hg(II), MeHg, and Hg(inert) are simulated with aqueous complexation, solubility, sorption, and kinetic transformation reactions. In addition, MERC4 conducts mass balance calculations for three user-defined solids. The current version of MERC4 does not include food chain components. It is presently undergoing limited inhouse and external testing, but has not been formally reviewed or released. A beta-test version of MERC4 was modified by PTI, Inc., to include simple bioaccumulation routines and successfully applied to Onondaga Lake, an urban lake in the Northeast. Fish Bioenergetics Model 2, developed at the University of Wisconsin Center for Limnology, was used to estimate Hg accumulation in the aquatic food chain based upon prey consumption, waste production, mortality, and fish growth. The food chain is composed of phytoplankton, zooplankton, macroinvertebrates, and seven fish species, including planktivores, demersals, and piscivores.

RMA-4 is a simple two-dimensional, depth-averaged finite-element water quality model that handles contaminant transport and first-order decay (King and Rachiele 1989). This model is linked with a compatible hydrodynamics program and software for mesh generation and post-processing. The University of California-Davis is modifying the RMA-4 model to simulate sediment and Hg components, including Hg(0), MeHg, and Hg(II). Both MeHg and Hg(II) are allowed to distribute between dissolved and particle-bound forms. Biological and chemical transformations of Hg from one component to another are modeled as either zero- or first-order sources or sinks. Among the transfer and transformation processes modeled are methylation, demethylation, volatilization, sorption-desorption, sedimentation, reduction, bio-uptake, atmospheric deposition, and diffusion.

Major Issues

Mercury fate is multimedia in scope. Because of the size and complexity of any general multimedia Hg model, efforts have generally been directed to individual media, although it is recognized that Hg can exchange between the atmosphere and surface water. Although aquatic food-web bioaccumulation models are often formulated separately from surface-water models, the nature of Hg dynamics requires a direct connection between the models. The major issues in constructing a Hg model are: 1) devising a proper and practical representation of the complex physical, chemical, and biological reactions, and 2) integration of the major components into an operational framework. The major issues in operating a Hg model are: 1) proper parameterization, given measurement and model uncertainty, and 2) spatial and temporal variability.

Current Studies

Both UC-Davis and ERD-Athens plan to pursue modeling investigations of Hg transport, fate, and bio-accumulation in Clear Lake. In a current contract, UC-Davis is developing a general Hg food-web model and parameterizing it for Clear Lake. UC-Davis plans to incorporate this model into a general biogeochemical modeling

system that simulates aqueous and benthic inorganic and MeHg concentrations throughout Clear Lake and exercise the modeling system to investigate consequences of potential remediation options. The resulting model will describe a simple aquatic food web that incorporates transfers to piscivorous birds and mammals. This model will be parameterized and validated with data from Clear Lake but will be designed so it can be applied to other aquatic systems by respecifying parameter values.

ERD-Athens is funding a National Research Council associate to investigate model linkage issues, particularly interactive coupling of hydrodynamic, water quality, and bioaccumulation models through parallel processing. Clear Lake will be the test system for this work. In addition, ERD-Athens has made plans to study Hg transport and fate within canal and marsh systems in the Everglades, in cooperation with EPA Region 4 R-EMAP studies. Some modeling components used in this study will be derived from the modeling package arising from the Clear Lake study. Two modeling tasks have been identified.

The goal of the first task is to predict the fate of Hg species in the sediments, water, and fish of both a selected canal system and a marsh system in the Everglades, based upon known sources. The first step in this task is to calibrate flow, sediment transport, and Hg transport in the selected aquatic systems. Based on results of the initial application and ongoing studies, the Hg transport model will be revised and extended. Food-web bioaccumulation will be simulated using the food-web model originally developed for Clear Lake.

The goal of the second modeling task is to predict the fate of Hg species in the sediments, water, and fishes of the Everglades, based upon known sources. The first step is to identify and code a simplified Hg dynamics model for linked canal-wetland-sediment compartments. This simplified model will be applied first in a simple compartment modeling framework for screening investigations, then later to the Everglades system as a whole, with proper hydrologic and atmospheric linkages specified from existing models. Issues of scale and model linkage will be investigated in both tasks.

Once the models for the canal, marsh, and Everglades system have been constructed, calibrated, and tested, sensitivity analyses will be conducted to explore the relative contributions of various sources and processes. Among potential sources to be analyzed are atmospheric deposition and exchange, oxidation of peat, methylation and exchange of historic benthic deposits, and runoff of nutrients and organic material from agricultural areas. Loading, transport, and benthic exchange under both average conditions and large-storm conditions will be studied.

Ongoing and planned hydrologic research and model development described in the chapter on modeling (in this document) should provide important input to application of these Hg models.

Information Needs

Critical questions

Level of process aggregation. Existing chemical fate models such as the TOXI5 component of WASP5 can simulate generic transformation processes among three chemicals as defined by the user. This model can be set up to describe partitioning, volatilization, oxidation, reduction, methylation, and demethylation reactions for dissolved, DOC-complexed, and sorbed phases of Hg(0), Hg(II), and MeHg. Models such as MCM and MERC4 add specific equilibrium complexation reactions to these kinetic reactions and allow more detailed chemical process description. A general modeling issue is matching the complexity of process description to the available scientific knowledge, available site-specific data, and level of analysis required.

- What value is gained in screening-level calculations and in management scenario analysis by increased levels of process description?

Level of spatial aggregation. The models outlined here have generally been parameterized for individual ponds, streams, and lakes. The computational networks generally have a longitudinal spatial resolution of 0.5-5 km (0.3-3 mi); the vertical resolution is typically 1-10 m (3.3-33 ft) in the water column and 1-100 cm (0.4-39 in) in the benthic sediment.

▸ What level of spatial aggregation in the benthic sediments is necessary to accurately capture the important biochemical transformation processes?

▸ How can a large network composed of canal and marsh elements be constructed to efficiently and accurately represent transport of Hg through large regions, such as a WCA or the Everglades as a whole?

Level of model linkage. The models described here represent chemical transport and fate processes in aquatic systems. Some have been linked to atmospheric and terrestrial models through external loading files. This is the most efficient approach when inter-media transport is predominantly feed-forward. Major questions to be answered in constructing a South Florida Hg modeling system include:

▸ What is the degree of feedback between aquatic, atmospheric, and terrestrial environments?

▸ How can these inter-media transfers can be efficiently and accurately represented?

Approach

Some of the existing Hg models are simplistic in their representation of Hg chemistry, while others represent only simple physical environments but incorporate a more realistic representation of Hg chemistry. MCM has become a standard for handling Hg components and reactions. Operational models are needed that can represent a complex physical environment and handle complex Hg chemistry in a manner similar to MCM. These are still under development and testing and require linkage with a food-web component.

Reliable diagnostic or predictive modeling depends to a great extent on accurate process descriptions. The most important areas of process uncertainty expected to affect overall Hg fate are highlighted below. The proper application of these models requires the specification of input data that describe and parameterize the environment being investigated. Data needs are also discussed below.

Site-specific data needs. For aquatic fate models, data needs include hydrogeometry, advective flows, dispersive transport, external loadings and boundary concentrations, and various chemical constants and environmental parameters. The chemical constants and environmental parameters required for Hg modeling will depend upon how the speciation and transformation processes in the model are formulated. Some environmental parameters expected to be important include pH, DO, DOC, sulfide, sulfate, and total dissolved solids.

Methylation and demethylation kinetics. The methyl forms of Hg are known to bioaccumulate strongly and provide the most risk to humans and wildlife. Most of the Hg delivered to the aquatic environment is inorganic. The internal production of MeHg, then, is a crucial process in any mechanistic Hg fate model. The form of the kinetic equations, dependencies on environmental parameters, and rate constants must be described and tested in a variety of aquatic environments.

Complexation with fine organics, DOC, and colloids. Those species of Hg that are complexed with dissolved or fine organic material are mobilized for transport but may be shielded from some loss processes. Good process models should be able to describe the binding capacity and strength of this material for various species of Hg. In addition, the biogeochemistry of DOC and fine organics in canals and wetlands must be described. Formation and loss processes must be quantified.

Sorption onto sediments. Those species of Hg that sorb onto suspended sediments can be deposited into the benthic environment and transformed or buried. Process models are needed that can accurately describe the sorption process for the important species of Hg. In addition, data are needed to characterize the sediments in South Florida so that their sorption capacity can be modeled. Sediment transport processes through canals and wetlands must be described, especially for silt and clay fractions. Deposition and scour processes must be described under both average conditions and during large-storm conditions.

Uptake by aquatic plants, phytoplankton. The amount of partitioning or uptake of Hg into the base of the aquatic food web drives subsequent bioaccumulation. Investigation is needed into how this can best be represented,

the coefficients or rates for Hg species entering phytoplankton and plants, and what environmental parameters might affect the kinetics.

Spatially distributed food-web model. The current generation of food-web models describes bioaccumulation in one place. For large or long aquatic systems with gradients of exposure concentrations, a spatially distributed food-web model will be necessary. Such a model would allow the user to specify a range for each fish species and age class. Plankton would be carried through the spatial network by advective currents. Overlapping ranges would be taken care of properly. Part of this effort requires the accurate biological description of the site being investigated. Modeling technology must be developed to facilitate representation of the biology and perform the bookkeeping properly.

Parallel linkage of aquatic fate and food-web models. Traditional aquatic chemical fate models do not include an internal food web. In these models, bioaccumulation calculations are executed following the aquatic fate calculations, as the aquatic concentrations are not usually affected significantly by the food web. Aquatic fate and bioaccumulation cannot be treated separately for MeHg, however, because a significant portion of the MeHg in the water column can be found in fish. Models such as MCM and Meridian have food-web equations built in, and the Wisconsin bioenergetics model has been used as a subroutine to MERC4. A general modeling linkage should be developed to allow the operation of specialized food-web models with spatially distributed aquatic fate models, including feedback between the two.

ATMOSPHERIC MERCURY FATE MODELING

Background

Atmospheric models of Hg transport and transformation are being constructed and used to determine human exposure to Hg from various anthropogenic sources. This section reviews operational atmospheric Hg fate models that could be adapted for use in South Florida. Present atmospheric Hg fate models are built upon the framework of existing chemical transport and fate models. These models can be modified to handle the special transfer and transformation reactions of Hg and its compounds. This chapter focusses on one long-range model that is being used to examine Hg transport, along with some of the process and data uncertainties encountered.

Following a decade of development in Europe and the U.S., the REgional Lagrangian Model of Air Pollution (RELMAP) was produced in 1984 (Eder et al. 1986; Clark et al. 1992). RELMAP is capable of simulating concentrations and wet and dry deposition patterns of SO_2, SO_4^{2-}, and fine and coarse particulate matter. In addition to the main model program, the complete RELMAP modeling system includes 19 preprocessing programs that prepare gridded meteorological and emissions data for use in the main program. Currently, the RELMAP is supported by EPA's Atmospheric Research and Exposure Assessment Laboratory.

The original sulfur version of RELMAP was recently modified to permit simulation of atmospheric Hg. The goal was to model the emission, transport, and fate of airborne Hg over the continental U.S. for the year 1989. Modifications to RELMAP for atmospheric Hg simulation were largely based on recent Lagrangian model developments in Europe (Petersen et al. 1994). The Hg version of RELMAP was developed to handle three species of Hg -- elemental (Hg^0), divalent (the mercuric ion, Hg^{++}), and particulate Hg (Hg_{part}) -- and carbon soot. Recent experimental work indicates both ozone (Munthe 1992) and carbon soot (Brosset and Lord 1991; Iverfeldt 1991; Lindqvist et al. 1991) are important in determining the wet deposition of Hg^0. Carbon soot, or total carbon aerosol, was included as a modeled pollutant in the Hg version of RELMAP to provide necessary information for the Hg^0 wet deposition parameterization. Observed O_3 air concentration data are used directly and not explicitly modeled. Methyl mercury was not included in the Hg version of RELMAP because it is not yet known if it has a primary natural or anthropogenic source, or if it is produced in the atmosphere.

Major Issues

Atmospheric models are generally used to estimate direct human exposure and provide loadings to surface water and soil. Volatile exchanges, however, could provide significant loadings from watersheds to the air. Although

terrestrial and aquatic fate models are often formulated separately from atmospheric models, the nature of Hg dynamics requires an interconnection between these models that is achieved only crudely at present. There are significant uncertainties about atmospheric Hg chemistry that could affect the accuracy of descriptions of deposition of Hg species at the local and regional scales.

Current Studies

Development of Eulerian model

The Atmospheric Characterization and Modeling Division of EPA/AREAL has proposed the development of a long-range atmospheric transport and transformation model using the Eulerian reference frame of the Regional Acid Deposition Model (RADM). This model will include internal nesting so subregions can be examined in detail within a framework that provides boundary concentrations from long-range transport. Given adequate support, 2 years would suffice to make this model operational.

Application of Eulerian model to South Florida

The Eulerian atmospheric transport model will be modified for Hg constituents and applied to the South Florida region. Vapor concentration and deposition data will be provided at a set of atmospheric monitoring stations covering eastern, central, and western South Florida. An inventory of Hg sources will provide the loadings to the model. A series of calibration simulations will cover the period of data collection and will focus on uncertain processes and model parameters. Following calibration, another series of simulations will be conducted to predict long-term atmospheric Hg trends given various management options.

Information Needs

Critical questions

Vertical Model Domain. The RELMAP model top is defined to be the maximum vertical extent of the convectively driven mixed layer. Monthly values defined from mixed-layer-height climatology are rough estimates of a meteorological phenomenon that may not exist in many situations. Although a surface-based mixed layer may be well defined, pollutants that persist in the atmosphere for long periods of time are certain to mix to some degree into the free atmosphere above the mixed-layer top. Elemental Hg deposits relatively slowly through precipitation processes due to its low water solubility, and its dry deposition appears to be minimal since it is in vapor form under normal atmospheric conditions. Elemental Hg does appear to be quite persistent in the atmosphere.

Because RELMAP does not simulate the flux of air or pollutants through the height of the mixed layer, which is fixed for each monthly simulation, the use of horizontally divergent/convergent wind fields to define the motion of the pollutant puffs can sometimes result in unrealistic instantaneous concentration fields. RELMAP was not designed to provide instantaneous realizations of pollutant concentration fields. Rather, it was designed for seasonal and annual simulations where the total effects of convergent and divergent wind fields can balance one another. There is, however, some uncertainty as to whether this balance actually occurs in all situations.

Aqueous Chemistry. The aqueous reduction-oxidation chemistry mechanism in the Hg version of RELMAP is applied only to the Hg^0 dissolved from the ambient air into the water droplet. Where significant concentrations of Hg^{++} from emissions exist in the ambient air, this Hg^{++} could be dissolved into the water droplet along with the Hg^0 and inhibit the scavenging of Hg^0. RELMAP simulation results described above indicate that Hg^{++} air concentrations are certainly lower than those for Hg^0 at the length scales of the RELMAP grid cells. However, the magnitude of the effect of ambient Hg^{++} on the Hg^0 oxidation scavenging is not yet well understood.

Another source of modeling uncertainty in aqueous chemistry relates to the fact that the aqueous chemical mechanisms were invoked only when and where precipitation was known to occur, and precipitation fields were only defined over land areas where precipitation observations were available. Significant wet transformation and removal of Hg may occur over oceanic areas where precipitation observations are not available, and it is possible that significant aqueous chemistry is occurring in nonprecipitating clouds.

Transport and diffusion. RELMAP simulates transport and diffusion only in the surface-based mixed layer. Vertical wind shear is small when the mixed layer is well defined, so under ideal conditions transport and diffusion are handled adequately. When the surface-based mixed layer is not well defined, however, vertical gradients in speed and/or direction of the wind may be present. These cannot be represented by the motion of individual Lagrangian puffs, whose layers remain vertically stacked. The most complete solution to the problem of vertical wind shear is the use of a Eulerian reference frame for numerical modeling. The EPA/AREAL has proposed development of a Toxics Linear Chemistry Model (TLCM) using the Eulerian reference frame of the RADM. Were this initiative to be adequately supported, the TLCM could be operational within 2 years.

Boundary fluxes of pollutants. Due to the RELMAP treatment of atmospheric pollutant loading as the combined effects of a population of discrete Lagrangian puffs and the long residence time of elemental Hg gas in the atmosphere, natural Hg emissions from the oceans and land surfaces cannot be explicitly modeled. The use of a Eulerian-type model would allow the definition of boundary fluxes of pollutants based on larger-scale model results or assumed background concentration levels.

Approach

The proper application of an environmental fate model requires specification of input data that describe and parameterize the environment being investigated. These data needs are discussed below.

Emissions inventory. Loadings of Hg introduced to the atmosphere from various sources, including coal-fired utilities, municipal waste incinerators, medical waste incinerators, and biomass burning, must be quantified and characterized. Knowledge of the oxidative state and physical form of the emitted Hg is important because these properties can influence the pattern of atmospheric dispersion and deposition. Knowledge of loadings of elemental, mercuric, and MeHg are desired. EPA/AREAL believes there is presently no adequate method for analyzing the species of Hg in emissions and, further, current stack sampling methods do not adequately characterize the chemical and physical form of Hg emissions as they manifest themselves on the regional scale. Chemical and physical transformations appear to be occurring in the exhaust flue and/or the local plume, and this creates a discrepancy between the Hg constituents measured in the stack and those measured in the atmosphere.

Wet and dry deposition fluxes. A spatial and temporal description of depositional loadings of elemental, mercuric, and MeHg is needed to drive aquatic fate models. While wet and dry fluxes may be measured at selected locations, a regional airshed model with local sources should be used with the observed data to more precisely understand loading patterns and distinguish among various local sources and regional and global background sources.

Mercury vapor concentrations and exchange rates. Elemental Hg in the air may undergo volatile exchange with concentrations in soil and water. This may provide a net source or sink to the ecosystem. Vapor concentrations in the air should be measured at selected monitoring locations; also, Hg vapor transport and reactions should be included in a regional airshed model. Experiments to quantify volatile exchange rates are needed.

Mercury plume chemistry. Physical and chemical reactions affecting Hg speciation in the plume must be described and quantified. These reactions are expected to affect the amount of Hg deposited locally in wetfall and the concentration of elemental Hg vapor that may exchange with the watershed. They may also help to explain the discrepancies in the chemical and physical form of Hg that often appear between stack gas measurements and ambient atmospheric measurements.

BIBLIOGRAPHY

Alberts, J.J., J.E. Schindler, R.W. Miller, and D.E. Nutter. 1974. Elemental mercury evolution mediated by humic acid. Science 184:895-897.

Ambrose, R.B., T.A. Wool, J.P. Connolly, and R.W. Schanz. 1987. WASP4, a hydrodynamic and water quality model. EPA/600/3-87/039. EPA Environmental Research Laboratory, Athens, Georgia.

Andren, A.W., and R.C. Harriss. 1973. Methyl mercury in estuarine sediments. Nature 245:256-257.

Andren, A.W., and R.C. Harriss. 1975. Observations on the association between mercury and organic matter dissolved in natural waters. Geochimica et Cosmochimica Acta 39:1253-1257.

Bachoon, D., and R. Jones. 1992. Soil Biology and Biochemistry 24:21-27.

Berman, M., and R. Bartha. 1986. Levels of chemical versus biological methylation of mercury in sediments. Bulletin of Environmental Contamination and Toxicology 36:402-404.

Billen, G., and R. Wollast. 1973. Transformations biologiques du mercure dans les sediments de la Sambre. Pages 191-232 *in* Rapport de synthese, project Sambre. Journees d'etude des 27 et 28 novembre 1972. CIPS. (as cited in: National Research Council. 1978. An Assessment of Mercury in the Environment. National Academy of Sciences, Washington, D.C.)

Bodaly, R.A., J.W.M. Rudd, R.J.P. Fudge, and C.A. Kelly. 1993. Mercury concentrations in fish related to size of remote Canadian Shield lakes. Canadian Journal of Fisheries and Aquatic Sciences 50:980-987.

Boudou, A., and F. Ribeyre. 1985. Experimental study of trophic contamination of *Salmo gairdneri* by two mercury compounds--$HgCl_2$ and CH_3HgCl--analysis at the organism and organ level. Water, Air, and Soil Pollution 26:137-148.

Brosset, C., and E. Lord. 1991. Hg in precipitation and ambient air: a new scenario. Water, Air, and Soil Pollution 56:493-506.

Callister, S.M., and M.R. Winfrey. 1986. Microbial methylation of mercury in upper Wisconsin River sediments. Water, Air, and Soil Pollution 29:453-465.

Cantillo, A.Y., T.P. O'Connor, and G.G. Lauenstein. 1993. South Florida environmental quality. NOAA Technical Memorandum NOS ORCA 75. NOAA, Silver Spring, Maryland.

Choi, S.-C., and R. Bartha. 1993. Cobalamin-mediated mercury methylation by *Desulfovibrio desulfuricans* LS. Applied and Environmental Microbiology 59:290-295.

Clark, T.L., P. Blakely, and G. Mapp. 1992. Model calculations of the annual atmospheric deposition of toxic metals to Lake Michigan. 85th Annual Meeting of the Air and Water Management Association, Kansas City, Missouri, June 23-37.

Compeau, G.C., and R. Bartha. 1984. Methylation and demethylation of mercury under controlled redox, pH and salinity conditions. Applied and Environmental Microbiology 48:1203-1207.

Compeau, G.C., and R. Bartha. 1985. Sulfate-reducing bacteria: principal methylators of mercury in anoxic estuarine sediment. Applied and Environmental Microbiology 50:498-502.

Davis, S.M., and J.C. Ogden, editors. 1994. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Delfino, J.J., T.L. Crisman, J.F. Gottgens, B.E. Rood, and C.D.A. Earle. 1993. Spatial and temporal distribution of mercury in Everglades and Okefenokee wetlands sediments. Final project report (two volumes). Department of Environmental Engineering Sciences, UF, Gainesville.

Depledge, M.H., and P.S. Rainbow. 1990. Models of regulation and accumulation of trace metals in marine invertebrates. Comparative Biochemistry and Physiology 97C:1-7.

D'Itri, F.M. 1972. The Environmental Mercury Problem. CRC Press, Inc., Boca Raton, Florida.

Driscoll, C.T., C. Yan, C.L. Schofield, R. Munson, and J. Holsapple. 1994. The mercury cycle and fish in the Adirondack lakes. Environmental Science & Technology 28:136A-143A.

Eder, B. K., D.H. Coventry, T.L. Clark, and C.E. Bollinger. 1986. RELMAP: a regional Lagrangian model of air pollution--users guide. Project report, EPA/600/8-86/013. EPA, Research Triangle Park, North Carolina.

Eisler, R. 1987. Mercury hazards to fish, wildlife, and invertebrates: a synoptic review. Biological Report 85(1.10). FWS, Washington, D.C.

Florida State University. 1990. Mercury Contamination in Florida: Impacts and Solutions. Proceedings of the Workshop. The Environmental Monitoring and Wet Environments Research Program, Center for Biomedical and Toxicological Research and Waste Management, FSU, Tallahassee, Florida.

Frederick, P.C., and M.G. Spalding. 1994. Factors affecting reproductive success of wading birds (Ciconiiformes) in the Everglades ecosystem. Pages 659-692 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and its Restoration. St. Lucie Press, Delray Beach, Florida.

Gavis, J., and J.F. Ferguson. 1972. The cycling of mercury through the environment. Water Research 6:989-1008.

Gill, G.A., and K.W. Bruland. 1990. Mercury speciation in surface freshwater systems in California and other areas. Environmental Science & Technology 24:1392-1400.

Gilmour, C.C., and E.A. Henry. 1991. Mercury methylation in aquatic systems affected by acid precipitation. Environmental Pollution 71:131-169.

Gilmour, C.C., E.A. Henry, and R. Mitchell. 1992. Sulfate stimulation of mercury methylation in freshwater sediments. Environmental Science & Technology 26:2281-2287.

Håkanson, L., A. Nilsson, and T. Andersson. 1988. Mercury in fish in Swedish lakes. Environmental Pollution 49:145-162.

Hudson, R.J.M., S.A. Gherini, and R.K. Munson. 1990. The MTL mercury model: a description of the model, discussion of scientific issues, and presentation of preliminary results. Section 8 *in* Mercury in Temperate Lakes Project. Annual Report for 1990 to Electric Power Research Institute, Palo Alto, California.

Hudson, R.J.M., S.A. Gherini, C.J. Watras, and D.P. Porcella. 1994. A mechanistic model of the biogeochemical cycle of mercury in lakes. Pages 473-523 *in* C.J. Watras and J.W. Huckabee, editors. Mercury Pollution: Integration and Synthesis. Lewis Publishers, Boca Raton, Florida.

Hurley, J.P., D.P. Krabbenhoft, C.L. Babiarz, and A.W. Andren. 1994. Cycling of mercury across the sediment-water interface of seepage lakes. Pages 425-449 *in* L.A. Baker, editor. Environmental Chemistry of Lakes and Reservoirs. Advances in Chemistry No. 237. American Chemical Society, Washington, D.C.

Iverfeldt, Å. 1991. Occurrence and turnover of atmospheric mercury over the Nordic countries. Water, Air, and Soil Pollution 56:151-165.

Jackson, T.A. 1988. The mercury problem in recently formed reservoirs of Northern Manitoba (Canada): the effects of impoundment and other factors on the production of methyl mercury by microorganisms in sediments. Canadian Journal of Fisheries and Aquatic Sciences 45:97-121.

Jernelov, A. 1970. Release of methyl mercury from sediments with layers containing inorganic mercury at different depths. Limnology and Oceanography 15:958-960.

Jonnalagadda, S.B., and P.V.V. Prasada Rao. 1993. Toxicity, bioavailability and metal speciation. Comparative Biochemistry and Physiology 106C:585-595.

Jurczyk, N.U. 1993. An ecological risk assessment of the impact of mercury contamination in the Florida Everglades. Master's Thesis. UF, Gainesville, Florida.

Kavanaugh, R.G., and T. Barkay. 1992. Methylation and demethylation processes in soils from the Florida Everglades. Interim Report for RARE Project. EPA Environmental Research Laboratory, Gulf Breeze, Florida.

King, I.P., and R.R. Rachiele. 1989. RMA4: a two dimensional finite element water quality model. Resource Management Associates, Lafayette, California.

Korthals, E.T., and M.R. Winfrey. 1987. Seasonal and spatial variations in mercury methylation and demethylation in an oligotrophic lake. Applied and Environmental Microbiology 53:2397-2404.

Lange, T.R., H.E. Royals, and L.L. Connor. 1993. Influence of water chemistry on mercury concentration in largemouth bass from Florida lakes. Transactions of the American Fisheries Society 122:74-84.

Lindberg, S.E., and R.C. Harriss. 1974. Mercury-organic matter associations in estuarine sediments and interstitial water. Environmental Science & Technology 8:459-462.

Lindqvist, 0., K. Johansson, M. Aastrup, A. Andersson, L. Bringmark, G. Hovsenius, L. Håkanson, Å. Iverfeldt, M. Meili, and B. Timm. 1991. Transformation and deposition processes (Chapter 6) *in* Mercury in the Swedish environment - recent research on causes, consequences and corrective methods. Water, Air, and Soil Pollution 55:49-63.

Lindqvist, O., and H. Rodhe. 1985. Atmospheric mercury -- a review. Tellus 37B:136-159.

Long, E.R., and L.G. Morgan. 1990. The potential for biological effects of sediment-sorbed contaminants tested in the National Status and Trends Program. NOAA Technical Memorandum NOS OMA 52.

Martin, J.L. 1992. MERC4: a mercury transport and kinetics model, beta test version 1.0, model theory and user's guide. Draft Report submitted to EPA Environmental Research Laboratory, Athens, Georgia.

Miskimmin, B.M., J.W.M. Rudd, and C.A. Kelly. 1992. Influence of dissolved organic carbon, pH, and microbial respiration rates on mercury methylation and demethylation in lake water. Canadian Journal of Fisheries and Aquatic Sciences 49:17-22.

Munthe, J. 1992. The aqueous oxidation of elemental mercury by ozone. Atmospheric Environment 26A:1461-1468.

Norstrom, R.J., A.E. McKinnon, and A.S.W. deFreitas. 1976. A bioenergetics-based model for pollutant accumulation by fish: simulation of PCB and methylmercury residue levels in Ottawa River yellow perch (*Perca flavescens*). Journal of the Fisheries Research Board of Canada 33:248-267.

Oremland, R.S., C.W. Culbertson, and M.R. Winfrey. 1991. Methyl mercury decomposition in sediments and bacterial cultures: involvement of methanogens and sulfate reducers in oxidative demethylation. Applied and Environmental Microbiology 57:130-137.

Petersen, G., Å. Iverfeldt, and J. Munthe. 1995. Atmospheric mercury species over central and northern Europe. Model calculations and comparison with observations from the Nordic air and precipitation network for 1987 and 1988. Atmospheric Environment 29:47-67.

PTI Environmental Services. 1994. Onondaga Lake RI/FS: mercury modeling report. Draft. PTI, Waltham, Massachusetts.

Richman, L.A., C.D. Wren, and P.M. Stokes. 1988. Fact and fallacies concerning mercury uptake by fish in acid stressed lakes. Water, Air, and Soil Pollution 37:465-473.

Robertson, D.E., D.S. Sklarew, K.B. Olsen, N.S. Bloom, E.A. Crecelius, and C.W. Apts. 1987. Measurement of bioavailable mercury species in fresh water and sediments. Electric Power Research Institute Report EA-5197.

Rodgers, D.W. 1994. You are what you eat and a little bit more: bioenergetic-based models of methylmercury accumulation in fish revisited. Pages 427-439 *in* C. Watras and J. Huckabee, editors. Mercury Pollution: Integration and Synthesis. Lewis Publications, Boca Raton, Florida.

Rodgers, D.W., and F.W.H. Beamish. 1982. Dynamics of dietary methylmercury in rainbow trout, *Salmo gairdneri*. Aquatic Toxicology 2:271-290.

Roelke, M.E., D.P. Schultz, C.F. Facemire, S.F. Sundlof, and H.E. Royals. 1991. Mercury contamination in Florida panthers. Report of the Florida Panther Subcommittee to the Florida Panther Interagency Committee.

Sorensen, E.M. 1991. Metal poisoning in fish. CRC Press, Boca Raton, Florida.

South Florida Water Management District. 1993. The effect of best-management practices (BMPs) on the loading of mercury species to the Everglades Protection Area. Project C-1. Section 319, Non-point Source Management Grants Program, SFWMD, West Palm Beach, Florida.

South Florida Water Management District, Florida Department of Environmental Protection, and U.S. Environmental Protection Agency Region 4. 1994. Mercury studies program plan for the Everglades Nutrient Removal Project. Draft.

Stober, J., D. France, W. McDaniel, D. Scheidt, D. Hicks, and J. Montanari. 1992. Draft Interagency Scope of Study of Mercury Contamination in the Everglades Ecosystem. Prepared for South Florida Policy Committee.

Stober, Q.J., R.D. Jones, and D.J. Scheidt. 1995. Ultra trace level mercury in the Everglades ecosystem, a multi-media canal pilot study. Water, Air, and Soil Pollution 80:991-1001.

Sugar Cane Growers Cooperative. 1994. The influence of phosphorus on mercury cycling and bioaccumulation in the Everglades. Draft report prepared by PTI Environmental Services, Waltham, Massachusetts.

Sundlof, S.F., M.G. Spalding, J.D. Wentworth, and C.K. Steible. 1994. Mercury in livers of wading birds (Ciconiiformes) in Southern Florida. Archives of Environmental Contamination and Toxicology 27:299-305.

U.S. Army Corps of Engineers. 1995. Florida's Everglades Program, Everglades Construction Project. Draft Programmatic Environmental Impact Statement. October 1995. COE, Jacksonville, Florida.

U.S. Environmental Protection Agency. 1993. R-EMAP: Regional Environmental Monitoring and Assessment Program. EPA/625/R-93/012. Office of Research and Development; Office of Science, Planning and Regulatory Evaluation; Center for Environmental Research Information, Cincinnati, Ohio.

Van Cappellen, P., and Y. Wang. In press. Metal cycling in surface sediments: modeling the interplay between transport and reaction. *In* H. Allen, editor. Metal Speciation and Contamination of Aquatic Sediments. Lewis Publications, Boca Raton, Florida.

Ware, F.J., H. Royals, and T. Lange. 1990. Mercury contamination in Florida largemouth bass. Proceedings of the Annual Conference of the Southeast Association of Fish and Wildlife Agencies 44:5-12.

Westöö, G. 1973. Methylmercury as percentage of total mercury in flesh and viscera of salmon and sea trout of various ages. Science 181:567-568.

Winfrey, M.R., and J.W.M. Rudd. 1990. Environmental factors affecting the formation of methyl mercury in low pH lakes. Environmental Toxicology and Chemistry 9:853-869.

Wood, J.M. 1974. Biological cycles for toxic elements in the environment. Science 183:1049-1052.

Wood, P.B., J. White, A. Steffer, J.M. Wood, and H.F. Percival. 1993. Mercury concentrations in tissues of Florida bald eagles. Final Report to FWS, Atlanta, Georgia.

Xu, H., and B. Allard. 1991. Effects of fulvic acid on the speciation and mobility of mercury in aqueous solutions. Water, Air, and Soil Pollution 56:709-717.

Zalups, R.K., and L.H. Lash. 1994. Advances in understanding the renal transport and toxicity of mercury. Journal of Toxicology and Environmental Health 42:1-44.

Zillioux, E.J., D.B. Porcella, and J.M. Benoit. 1993. Mercury cycling and effects in freshwater wetland ecosystems. Environmental Toxicology and Chemistry 12:2245-2264.

PESTICIDES AND URBAN CONTAMINANTS

INTRODUCTION

The population of the southeast United States has experienced the highest growth rate in the nation in recent decades. Florida, in particular, has seen a dramatic population increase since the late 1970s, which has led to increased urbanization and more intense utilization of arable land for agriculture. One consequence of increased agriculture and population growth in South Florida is the potential for toxic effects in estuarine and marine areas caused by pesticides and contaminants associated with urbanization, such as PAHs, PCBs, and heavy metals.

CURRENT-USE PESTICIDES

Pesticide use in South Florida agriculture likely presents one of the greatest risks to the quality of estuarine and marine receiving waters due to the intense degree of farming and cultivation of crops that require large amounts of pesticides. A recent summary by Pait et al. (1992) compiled information on pesticide toxicity to estuarine organisms and pesticide usage in estuarine watersheds in 1987. The study ranked estuarine watersheds in the U.S. based on the toxic hazard resulting from pesticides. This was assessed by summing the risk from a specific pesticide to estuarine organisms determined from fish and crustacean LC_{50} values, soil half-life, and bioaccumulation potential. The total hazard was estimated by summing the risk for each pesticide used in the watershed, multiplied by the amount used per unit area, normalized to the size of the watershed. The two estuaries in the Nation with the greatest pesticide hazard were in South Florida -- Rookery Bay (in Subregion 8) and Biscayne Bay (in Subregion 9). Rookery Bay ranked first, based on its small watershed and use of high-hazard pesticides. In addition, South Ten Thousand Islands (in Subregion 8) and Charlotte Harbor (in Subregion 10) ranked sixth and ninth in the U.S., respectively.

Most of the hazard associated with pesticide use in South Florida is due to one compound -- endosulfan. Endosulfan, assigned the highest hazard factor by Pait et al. (1992), is very heavily used in South Florida estuarine drainage areas (> 105,000 lbs in 1987). The endosulfan applied in South Florida accounts for 34% of the total used in the U.S. In the drainage areas of Biscayne Bay, Charlotte Harbor, South Ten Thousand Islands, and Rookery Bay, the amounts of endosulfan applied were 12%, 12%, 6%, and 4% of the U.S. total, respectively.

Endosulfan is a general-use cyclodiene insecticide containing two isomers (endosulfan I and II). It has a fairly short half-life in seawater (ca. 1 week), with the degradation affected by pH (Cotham and Bidleman 1989). Degradation in seawater is primarily to endosulfan sulfate, although in the alkaline environment of seawater (ca. pH 8) there is likely some base hydrolysis to endosulfandiol. Endosulfan is moderately hydrophobic, with a log ocanol/water partition coefficient (log K_{ow}) of 3.6 (Suntio et al. 1988). Work by Cotham and Bidleman (1989) suggests endosulfan may be more persistent if it is bound to sediments versus dissolved in water.

Endosulfan is a supertoxic (e.g., 96h LC_{50} < 10 μg/L) organochlorine insecticide that is equally toxic to fish and crustaceans. Studies have found 96h LC_{50} values for estuarine fish of 1.15 μg/L for adults and 0.23 μg/L for juveniles (Baughman 1986; Trim 1985; Moore 1988). Similarly, 96h LC_{50} values for crustaceans were approximately 1 μg/L. Currently, EPA and State of Florida water quality criteria for endosulfan are 0.0085 μg/L in surface waters. Scott et al. (1992) showed non-point source agricultural runoff containing endosulfan concentration of > 0.50 μg/L was acutely toxic to fish and shellfish in tidal creeks downstream of agricultural vegetable farming areas. The major degradation product of endosulfan, endosulfan sulfate, has been shown to be even more toxic than the parent compound to some aquatic species (Schimmel et al. 1977).

Endosulfan has also been shown to be an estrogen-mimicking compound (Sota et al. 1994). The effects of such compounds on humans and wildlife are discussed in Colborn and Clement (1992), and their long-term ramifications on animal populations are potentially serious.

The fate and actual effects of the endosulfan used in South Florida are poorly understood. Most efforts examining this compound have taken the form of surface water quality monitoring. In Florida, endosulfan was the third most commonly detected current-use agrichemical in surface waters and was found at concentrations of 22-1861 $\mu g/L$ (Shahane 1994). It was also the most commonly detected current-use agrichemical in sediments, at concentration of 0.7-230 $\mu g/g$. Endosulfan has also been detected in areas far from sites of application, suggesting this compound may be more persistent in the environment than previously believed thereby increasing the likelihood of long-range transport. For instance, endosulfan I was detected in Sable Island, Nova Scotia, air at concentrations of 2-91 pg/m^3 (Bidleman et al. 1992) and in Bering Sea surface waters in the low ng/m^3 range (Bidleman, pers. comm.). Persistence of this compound and magnitude of its long-range transport, either through the atmosphere or ocean currents, are critical information needs.

CONTAMINANTS FROM URBAN SOURCES

Urban non-point source runoff remains a major issue in South Florida given the large population densities in the coastal zone ($>3000/mi^2$). The major contaminants in urban runoff are PAHs (Fulton et al. 1993; Hoffman et al. 1984; Kucklick and Bidleman 1994). The major sources of PAH pollution in estuarine/marine environments are runoff from roadways of combustion products from vehicle emissions and discharges from outboard engines particularly near marinas (Fulton et al. 1993; Kucklick and Bidleman 1994). Atmospheric deposition of PAHs may also be a major source of urban pollution, as demonstrated in Chesapeake Bay (Leister and Baker 1994). Many PAHs are endocrine disrupting chemicals causing alterations in growth, survival, and development in some wildlife species (Colborn et al. 1993). In addition, PAHs in sediments have been implicated as a primary cause of cancer and hepatic lesions in benthic fishes (Johnson et al. 1993)

INFORMATION NEEDS AND RECOMMENDED APPROACH

The effects of contaminants present at low levels in the environment on ecosystem health and function are both poorly understood and potentially difficult to quantify. The environmental consequences of contaminant exposure is only in rare instances manifested in an acute, lethal response. Ambient toxicity to estuarine organisms resulting from low-level exposures are likely more subtle and occur at the population level, resulting in decreased fecundity, increased predation, or other factors that affect mortality. Therefore, efforts to examine effects of contaminants in South Florida must couple knowledge of ecosystem processes with the effects of contaminants from chronic toxic exposure. In other words, examining contaminant effects should not simply become a monitoring effort. Modeling should also be incorporated up front to integrate different disciplines and provide a future basis for decision making. Examining the effects of contaminants should also take into account the effects of land use on contaminant release and effects. Future development in South Florida should be directed towards land-use patterns that minimize contaminant effects or enhance ecosystem function. The approach to determine the fate and effects of organic contaminants on the South Florida Ecosystem is outlined below. Figure 6 summarizes information needs in relation to restoration and science objectives.

- **Determine the amounts and types of pesticides used in South Florida, updating existing pesticide survey records.**

The survey by Pait et al. (1992) compiled pesticide usage information for estuarine drainage areas in the U.S. This was an indirect calculation of the amounts of pesticides used in the given areas based on several factors, including percent of each crop type and typical application rates. A logical starting point for estimating the potential for pesticide loss from South Florida farms would be a comprehensive measurement of the amounts of pesticides applied. Such an investigation should cover several years to examine variability and trends in pesticide usage. This information would be vital for evaluating the environmental fate of pesticides through a mass balance approach and predictions based on soil-loss models.

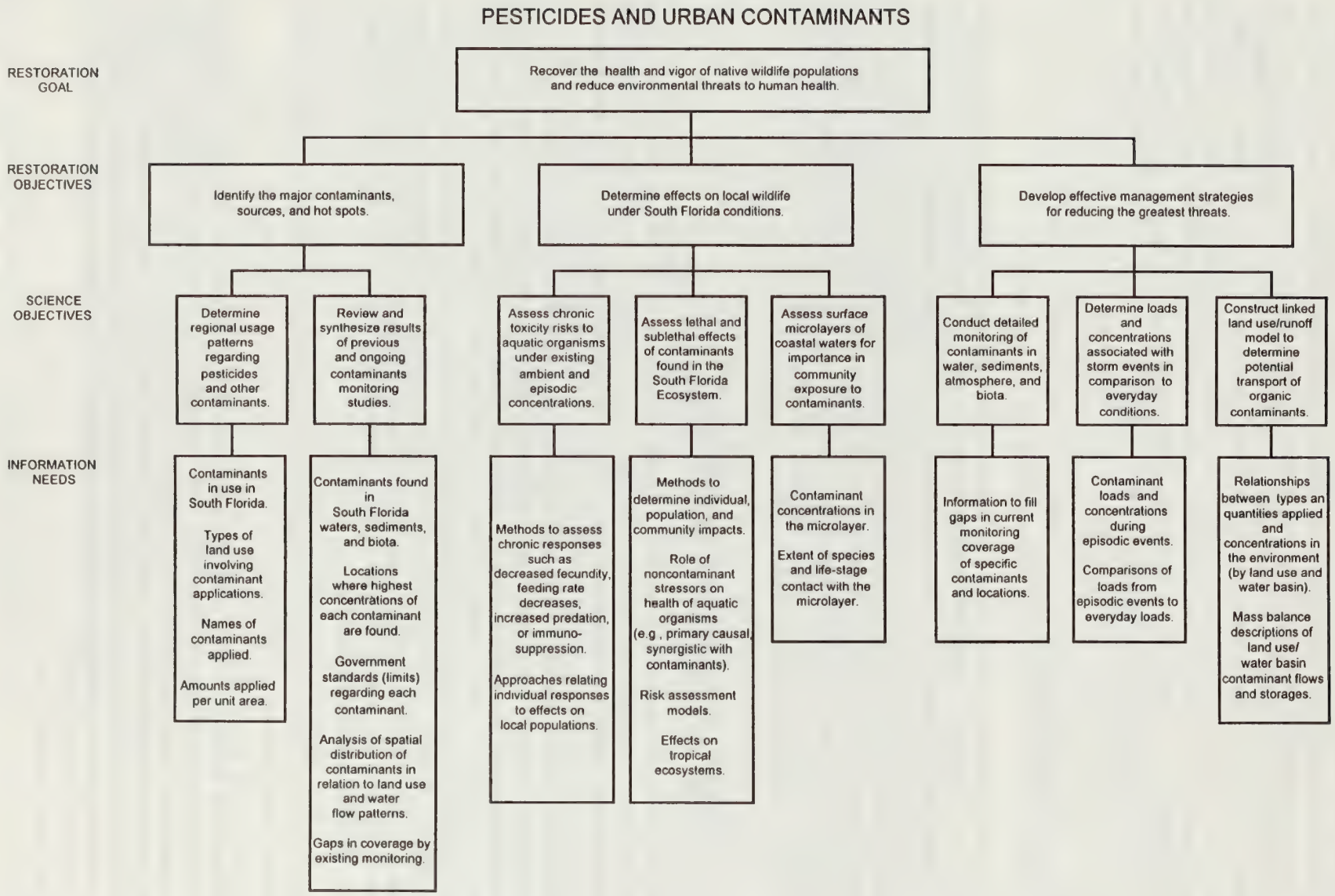

PESTICIDES AND URBAN CONTAMINANTS
RESTORATION GOAL
Recover the health and vigor of native wildlife populations and reduce environmental threats to human health.
RESTORATION OBJECTIVES
Identify the major contaminants, sources, and hot spots.
Determine effects on local wildlife under South Florida conditions.
Develop effective management strategies for reducing the greatest threats.
SCIENCE OBJECTIVES
Determine regional usage patterns regarding pesticides and other contaminants.
Review and synthesize results of previous and ongoing contaminants monitoring studies.
Assess chronic toxicity risks to aquatic organisms under existing ambient and episodic concentrations.
Assess lethal and sublethal effects of contaminants found in the South Florida Ecosystem.
Assess surface microlayers of coastal waters for importance in community exposure to contaminants.
Conduct detailed monitoring of contaminants in water, sediments, atmosphere, and biota.
Determine loads and concentrations associated with storm events in comparison to everyday conditions.
Construct linked land use/runoff model to determine potential transport of organic contaminants.
INFORMATION NEEDS
Contaminants in use in South Florida.
Types of land use involving contaminant applications.
Names of contaminants applied.
Amounts applied per unit area.
Contaminants found in South Florida waters, sediments, and biota.
Locations where highest concentrations of each contaminant are found.
Government standards (limits) regarding each contaminant.
Analysis of spatial distribution of contaminants in relation to land use and water flow patterns.
Gaps in coverage by existing monitoring.
Methods to assess chronic responses such as decreased fecundity, feeding rate decreases, increased predation, or immuno-suppression.
Approaches relating individual responses to effects on local populations.
Methods to determine individual, population, and community impacts.
Role of noncontaminant stressors on health of aquatic organisms (e.g., primary causal, synergistic with contaminants).
Risk assessment models.
Effects on tropical ecosystems.
Contaminant concentrations in the microlayer.
Extent of species and life-stage contact with the microlayer.
Information to fill gaps in current monitoring coverage of specific contaminants and locations.
Contaminant loads and concentrations during episodic events.
Comparisons of loads from episodic events to everyday loads.
Relationships between types an quantities applied and concentrations in the environment (by land use and water basin).
Mass balance descriptions of land use/ water basin contaminant flows and storages.

Figure 6. Goal, objectives, and information needs for efforts on pesticides and urban contaminants.

- **Review and synthesize previous and ongoing monitoring studies of organic contaminants in South Florida water, biota and sediments.**

Several agencies are currently examining the fate and effects of pesticide use in South Florida, including the South Florida Water Management District, U.S. Geological Survey, National Marine Fisheries Service, EPA, and several county environmental management units such as Dade County's Department of Environmental Resources Management. Efforts need to be continued and expanded to foster the communication of findings among these agencies, coordinate activities, and prevent replication of effort.

- **Construct a linked land-use runoff model to examine the potential for offsite transport of organic contaminants, especially endosulfan.**

As part of the synthesis of current and past work, a framework must be developed to incorporate both existing data and provide a platform for examining scientific and management issues. This can be best accomplished by using a linked land-use water quality model. A successful approach applied to smaller systems has been a GIS land-use model coupled to process-oriented water quality models (Chen et al. 1993; Reckhow 1994). The ultimate goal would be to help direct future monitoring and process studies based on data needs revealed by the model and pinpoint those ecological indicators that best express ecosystem function. The model could potentially incorporate ecological process information, such as recruitment, and therefore provide a method to examine interactions between contaminants and ecosystem processes. Admittedly, models often do not give the level of certainty needed to make precise forecasts, but they are valuable for providing insight in the management decision-making processes.

- **Conduct detailed monitoring of contaminants in water, sediments, biota, and atmosphere, especially during the active pesticide application period.**

This effort is needed for two reasons. First, there has not been a comprehensive survey of these environmental media in South Florida for current-use agrichemicals, especially endosulfan, or other contaminants associated with urbanization, such as PAHs. Results from one or two year-long seasonal monitoring efforts would help focus on those compounds that present the greatest risk. Second, results from a comprehensive monitoring effort are needed to calibrate land-use runoff models in the initial stages of model development and validate the model in subsequent years.

- **Conduct a detailed monitoring of environmental media for pesticides and urban contaminants during episodic events.**

Recent work by Scott et al. (1992) indicates magnitude and timing of pesticide application and urban runoff events have a large effect on the impact of the pesticides on adjacent estuarine communities. For instance, most of the acute effects of contaminants have been shown to be associated with stormwater discharge. Any contaminant monitoring in South Florida must include investigation of the amounts released during storm events. This effort should be accompanied by an evaluation of sensitive estuarine and marine species whose occurrence or movement may coincide with runoff events.

- **Assess chronic toxicity risks to aquatic organisms at ambient contaminant levels.**

Most contaminants are present in the environment at concentrations that are not acutely toxic. Some contaminants, however, can lead to chronic responses such as decreased fecundity, feeding rate decreases, increased predation, or immunosuppression. These effects are difficult to quantify beyond the organismal level. A method needs to be developed that assesses these effects at the ecosystem level. This could be an ecosystem model, for instance, with chronic contaminant effects incorporated into processes that affect carbon flow and thereby ecosystem function.

- **Determine the quantities of pesticides and their fates in environmental media relative to the amounts applied.**

To properly manage pesticide use in South Florida, a mass balance estimate must be made starting with the amounts of pesticides applied to farm fields and their fates in biota, soils, groundwater, surface water, and the atmosphere. A mass balance description may be a short-term objective if applied to a small watershed. It may also be a long-term objective as more use and monitoring data become available and are incorporated into a mass balance model for specific contaminants in all of South Florida. The major benefit of a mass balance model is that the most controllable contaminant sources are identified.

- **Assess the importance of surface microlayers as regions of localized pesticide enrichment in terms of toxicity both in Florida Bay and offshore.**

The thin microlayer of surface waters of the oceans, including Florida Bay, is enriched in dissolved and organic carbon. This microlayer may serve as a food source for plankton and may be important in offshore coastal food chains. Additionally, this microlayer is often enriched in chemical contaminants relative to underlying surface waters and may pose a toxicological hazard to aquatic organisms, particularly zooplankton and early life history stages of fish (eggs and juveniles) and shellfish (larvae and juveniles) that spawn offshore (Hardy et al. 1987). Snedecor (in preparation) reported that surface water samples from oceans around the world were enriched with persistent organochlorine pesticides. Endosulfan, detected in >50% of all surface microlayer samples, was the most frequently measured pesticide. The studies on microlayer surface slicks by Snedecor and others need to be expanded in Florida Bay and other coastal regions of South Florida.

Of particular concern is the possibility that, because the Gulf Stream is so close to the South Florida coast, there is significant transport of pesticides into the Gulf Stream, which can then transport them to higher latitudes. This may result in exposure of many marine organisms to contaminants entrained in these surface microlayer slicks, including marine mammals, sea turtles, fish/fish eggs, shellfish, and plankton. Many of the contaminants detected in surface microlayers are potential endocrine disrupting chemicals. The potential exists for early life history stages of fish and shellfish to be exposed to chemical contaminants in these surface microlayers, which may affect survival, growth, and development of these organisms and impact commercially and recreationally important fishery species.

Monitoring studies are needed to assess this potential hazard in offshore coastal waters of Florida Bay. Laboratory studies are also needed to assess the potential toxicological hazard surface microlayers pose to aquatic organisms. These studies should: 1) Determine and differentiate the toxicological hazards microlayers pose to aquatic organisms that may spend only a portion of their life cycle in the microlayer region; 2) compare contaminant uptake in different trophic levels (primary, secondary and tertiary consumers) feeding or otherwise interacting with microlayers; and 3) determine the importance of surface-layer contaminant exposure on fish eggs exposed continuously and discontinuously (e.g. microlayer-associated) to chemical contaminants. These studies would help define the potential impacts contaminants entrained in surface microlayers pose to living marine resources.

- **Assess lethal and sublethal effects in Florida Bay of pesticides and other contaminants such as metals and PAHs at the organism, population, and ecosystem levels to develop appropriate risk assessment models and environmental management strategies.**

The focus should be to develop methods to determine individual and cumulative impacts of a variety of chemical contaminants as well as impacts of noncontaminant stressors; e.g., altered salinity (either hyper- or hyposaline conditions), altered hydroperiods, increased physical disturbance from boat wakes and habitat alterations, and reduced habitat suitability/acreage. The distinction between contaminant and noncontaminant stressors is important. If significant population decline is observed in a species, studies should be designed to assess and measure contaminant stressors directly in the species affected (e.g., tissue bioaccumulation), along with surface water, sediment, and air samples to determine the contaminant sources and the degree to which the contaminant(s) are affecting the living marine resources. Laboratory toxicity tests, mesocosms, *in situ* field bioassays, and population/community sampling are procedures that should be used to determine the degree to which the observed population decline is linked to a specific contaminant(s).

Where chemical contamination is observed and negative impacts are suspected, environmental management should focus on reducing contaminant loadings with an emphasis on a mass balance approach. This will help identify contaminant sources (such as agricultural pesticide non-point source runoff, urban non-point source runoff, atmospheric deposition, and recycled contaminants from sediments) and those sources contributing the largest portion of contaminant input. Coupled with a toxic equivalency approach, this will help determine the cumulative risk. At the same time, studies should focus on a similar mass balance approach to identify environmental changes in habitat quantity and quality (e.g., wetlands functionality, salinity regime, hydrographic regime, dissolved oxygen, turbidity) and to systematically evaluate the potential effects of each type of change using laboratory, mesocosm, and *in situ* field approaches. If both contaminant and noncontaminant stressors are similarly important in causing the observed population decline, environmental management should focus on both contaminant reduction and other habitat restoration methodologies. It is particularly important to develop these risk assessment approaches in tropical ecosystems, including coral reef, seagrass, and mangrove communities in South Florida and Florida Bay.

- **Assess the effects of endocrine disrupting chemicals on tropical ecosystems.**

Many chemical contaminants are potential endocrine disrupting chemicals, acting as either estrogen or androgen mimics in fish and other vertebrates and ecdysone/molting hormone mimics in crustaceans. Particular emphasis should be placed on contaminants such as endosulfan and PAHs, which are found in the marine environs of South Florida and Florida Bay. Studies should focus on linking specific biomarkers of endocrine dysfunction, reproduction, and population dynamics for key indicator species to specific endocrine disrupting chemicals.

All the above information is necessary to evaluate long-term organic contaminant issues in South Florida. Two items should be addressed immediately to provide an initial assessment of the risk of pesticides to the South Florida Ecosystem. First, a better quantitative assessment of the types and amounts of pesticides used is critically needed to refine the toxic potential of pesticides based on the amounts expected to be released to the environment. The effort should be coincident with the synthesis and evaluation of water quality monitoring data to determine the actual amounts of pesticides leaving the fields and entering estuarine and marine waters. Second, information, either from literature sources or laboratory studies, specific to tropical and subtropical estuarine species needs to be summarized relative to the pesticides currently used in South Florida. Coupling these two sets of information will provide the basis of an initial risk assessment.

BIBLIOGRAPHY

Baughman, D.S. 1986. The acute toxicity of insecticides associated with agricultural runoff to the grass shrimp, *Palaemonetes pugio*. M.S. thesis. University of South Carolina. 70 pages.

Bidleman, T.F., W.E. Cotham, R.F. Addison, and M.E. Zinck. 1992. Organic contaminants in the northwest Atlantic atmosphere at Sable Island, Nova Scotia, 1988-89. Chemosphere 24:1389-1412.

Chen, Y.D., S.C. McCutcheon, T.C. Rasmussen, W.L. Nutter, and R.F. Carsel. 1993. Integrating water quality modeling with ecological risk assessment for nonpoint source pollution control: a conceptual framework. Water Science and Technology 28:431-440.

Colborn, T., and C. Clement, editors. 1992. Chemically-Induced Alterations in Sexual and Functional Development: The Wildlife/Human Connection. Advances in Modern Environmental Toxicology, Volume 21. Princeton Scientific Publishing Company, Inc., Princeton, New Jersey.

Colborn, T., F.S. VonSaal, and A.M. Soto. 1993. Developmental effects of endocrine-disrupting chemicals in wildlife and humans. Environmental Health Perspectives 101:379-384.

Cotham, W.E. and T.F. Bidleman. 1989. Degradation of malathion, endosulfan and fenvalerate in seawater and seawater/sediment microcosms. Journal of Agricultural and Food Chemistry 37:824-828.

Fulton, M., G. Scott, T. Bidleman, and B. Nagabe. 1993. An examination of nonpoint source urban runoff in two small high salinity estuaries of the southeast United States. Archives of Environmental Contamination and Toxicology 25:476-784.

Hardy, J.T., E.A. Crecelius, L.D. Antrim, V.L. Broadhurst, C.W. Apts, J.M. Gurtisen, and T.J. Fortman. 1987. The sea-surface microlayer of Puget Sound: Part II. Concentrations of contaminants and relation to toxicity. Marine Environmental Research 23:241-271.

Hoffman, E.J., G.L. Mills, J.S. Latimer, and F.G. Quinn. 1984. Urban runoff as a source of polycyclic aromatic hydrocarbons to coastal waters. Environmental Science and Technology 18:580-587.

Johnson, L.L., C.M. Stehr, O.P. Olson, M.S. Myers, S.M. Pierce, C.A. Wigren, B.B. McCain, and U. Varanasi. 1993. Chemical contaminants and hepatic lesions in winter flounder (*Pleuronectes americanus*) from the northeast coast of the United States. Environmental Science and Technology 27:2759-2771.

Kucklick, J.R., and T.F. Bidleman. 1994. Organic contaminants in Winyah Bay, South Carolina I: Pesticides and polycyclic aromatic hydrocarbons in subsurface and microlayer waters. Marine Environmental Research 37:63-79

Leister, D.L., and J.E. Baker. 1994. Atmospheric deposition of organic contaminants to the Chesapeake Bay. Atmospheric Environment 28:1499-1520.

Moore, D.M. 1988. An integrated laboratory and field study of nonpoint source agricultural insecticide runoff and its effects on the grass shrimp, *Palaemonetes pugio* (Holthius). Ph.D. dissertation. University of South Carolina. 262 pages.

Pait, A.S., A.E. DeSouza, and D.R.G. Farrow. 1992. Agricultural Pesticide Use in Coastal Areas: A National Summary. Strategic Environmental Assessments Division, NOAA, Rockville, Maryland. 112 pages.

Reckhow, K.H. 1994. Water quality simulation modeling and uncertainty analysis for risk assessment and decision making. Ecological Modelling 72:1-20.

Scott, G.I., M.H. Fulton, M.C. Crosby, P.B. Key, J. Daugomah, J.T. Waldren, E.D. Strozier, C.J. Louden, G.T. Chandler, T.F. Bidleman, K.L. Jackson, T.W. Hampton, T. Hoffman, A. Shulz, and M. Bradford. 1992. Agricultural insecticide runoff effects on estuarine organisms: Correlating laboratory and field toxicity tests, ecophysiology, and ecotoxicology biomonitoring. Final Report to EPA, Gulf Breeze, Florida.

Shahane, A.N. 1994. Pesticide detections in surface waters of Florida. Pages 408-416 *in* A.R. Dutton, editor. Toxic Substances and the Hydrologic Sciences. American Institute of Hydrology, Minneapolis, Minnesota.

Shimmel, S.C., J.M. Patrick Jr., and A.J. Wilson Jr. 1977. Acute toxicity to and bioconcentration of endosulfan by estuarine animals. Pages 241-252 *in* Aquatic Toxicology and Hazard Evaluation. American Society of Testing and Materials, Philadelphia, Pennsylvania.

Sota, A.M., K.L. Chung, and C. Sonnenschein. 1994. The pesticides endosulfan, toxaphene, and dieldrin have estrogenic effects on human estrogen-sensitive cells. Environmental Health Perspectives 102:380,383.

Suntio, L.R., W.Y. Shiu, J. Seiber, and D. Glotfelty. 1988. Critical review of Henry's Law constants for pesticides. Reviews of Environmental Contamination and Toxicology 103:1-51.

Trim, A.H. 1985. The acute toxicity of insecticides present in non-point source, agricultural runoff on the mummichog, *Fundulus heteroclitus*, with an emphasis on the sublethal effects of endosulfan. M.S. thesis. University of South Carolina. 75 pages.

MODELS

INTRODUCTION

The development and use of models is an important component of the scientific support for South Florida Ecosystem Restoration. Models are essential tools for understanding and managing complex systems. One major use of models will be as assessment tools to evaluate proposed alternative structural and operational plans by predicting how the system and its various components will respond to the changes. The most valuable models will be those that can be used not only for assessment but also to help organize information, identify information gaps, clarify and test hypotheses, determine the mutual compatibility and consistency of several hypotheses, and evaluate potential direct and indirect effects of known or suspected causal relationships.

Five general classes of models -- hydrologic, hydrodynamic, meteorologic, ecologic, and water quality/transport -- are discussed in this chapter. Figure 7 shows how these models are connected and how they will provide the information needed by other models and, in turn, use data generated by other models. In some cases, two-way exchanges of information between models will occur. The types of information required are shown in Figure 8 in relation to the science objectives of the modeling efforts.

Hydrologic models translate precipitation into water depths, water flows, and volumes of water in storage. The outputs of hydrologic models provide input to all other types of models. Hydrologic models simulating the natural system prior to drainage will provide perspective on how the natural system operated in the absence of canals, levees, and control structures and before the thick deposits of organic soils had subsided. Models that allow changes to be made in canals, levees, water control structures, and their operations make it possible to test proposed alternative configurations of the water management system for their ability to reestablish more natural-like hydropatterns (i.e., timing and duration of surface water; timing, volume, and location of freshwater flows to wetlands and the coast).

Hydrodynamic models of Florida Bay and other coastal areas can translate freshwater inflows from upstream models into salinity and circulation patterns. Once this connection is made, ecologic models and supporting studies can be used to determine how proposed modifications in the C&SF Project will affect estuarine resources in Florida Bay. Hydrodynamic and transport models also will be needed in freshwater and coastal wetlands to approximate the distribution of nutrients and other waterborne materials such as particulate and dissolved organic carbon and contaminants.

Hydrologic and transport models of the mangrove zone will estimate freshwater flows to estuaries and water depths and salinities within the mangrove zone as dynamic functions of freshwater inflow from upstream and tidal and nontidal forces influencing coastal sea levels. Such models, used to drive forage fish and wading bird models, will help scientists and managers gain insight on how natural and anthropogenic changes in freshwater inflow may affect recruitment to offshore fisheries and colony site selection and fledgling production by wading birds. These models also will provide critical information on freshwater flows to Florida Bay and the Lower Southwest Coast. Flow estimates are critical to development and operation of hydrodynamic models of Florida Bay and adjacent coastal areas.

Meteorologic modeling, combined with radar (NEXRAD) technology, can improve the estimate of precipitation over South Florida and simulate precipitation in areas for which data are lacking. This is critical input for hydrologic and hydrodynamic models. Modeling can also provide estimates of routine conditions and weather events such as freezes and storms. A meteorologic model, which requires information on surface water, soil moisture, and land cover, can eventually be coupled to a natural system model and used to estimate the extent to which drainage and land-cover changes have affected South Florida's rainfall. It can also be coupled to models of alternative hydrologic strategies to determine how they would be expected to affect rainfall.

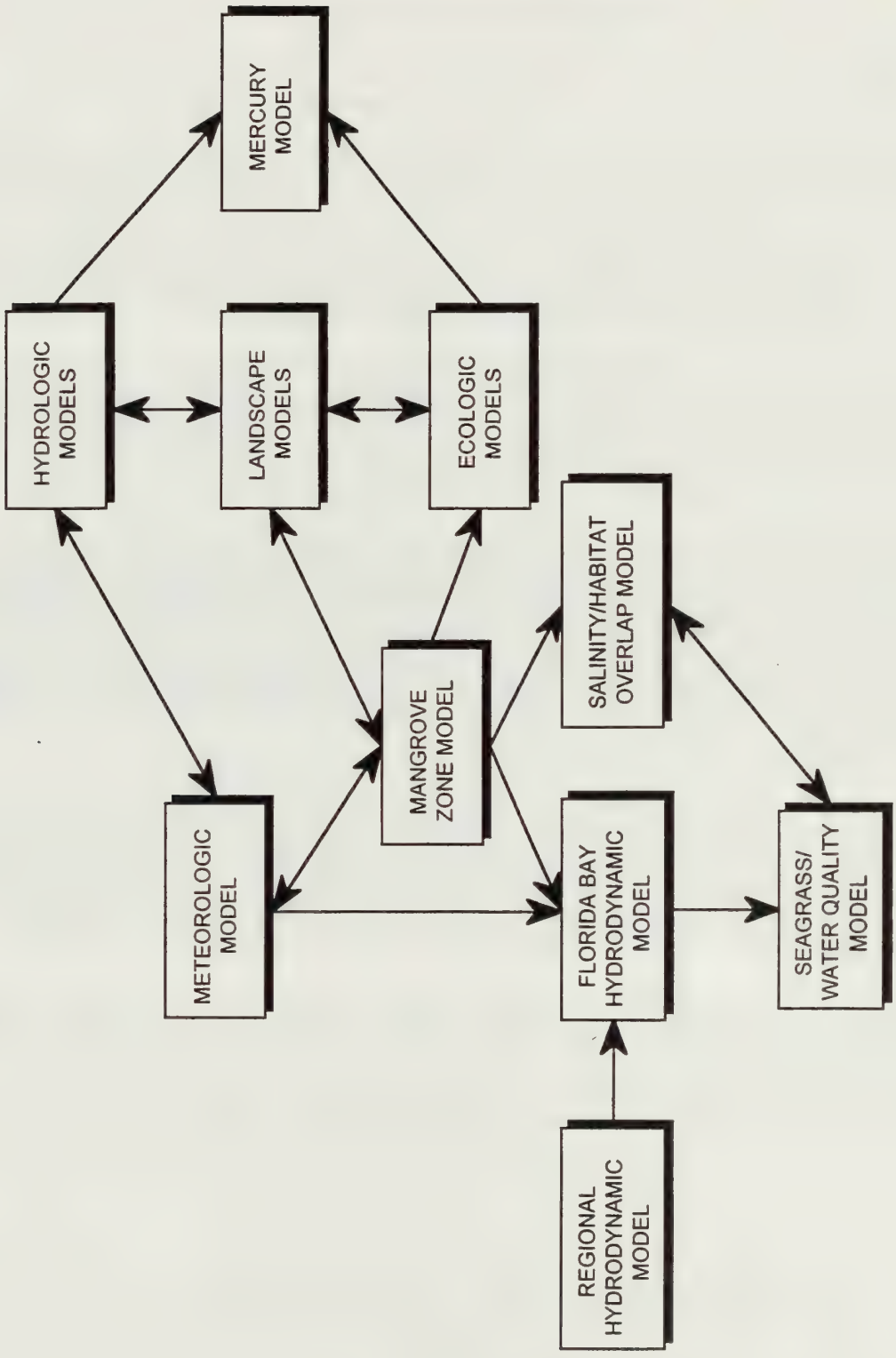


Figure 7. Pathways of model interdependencies.

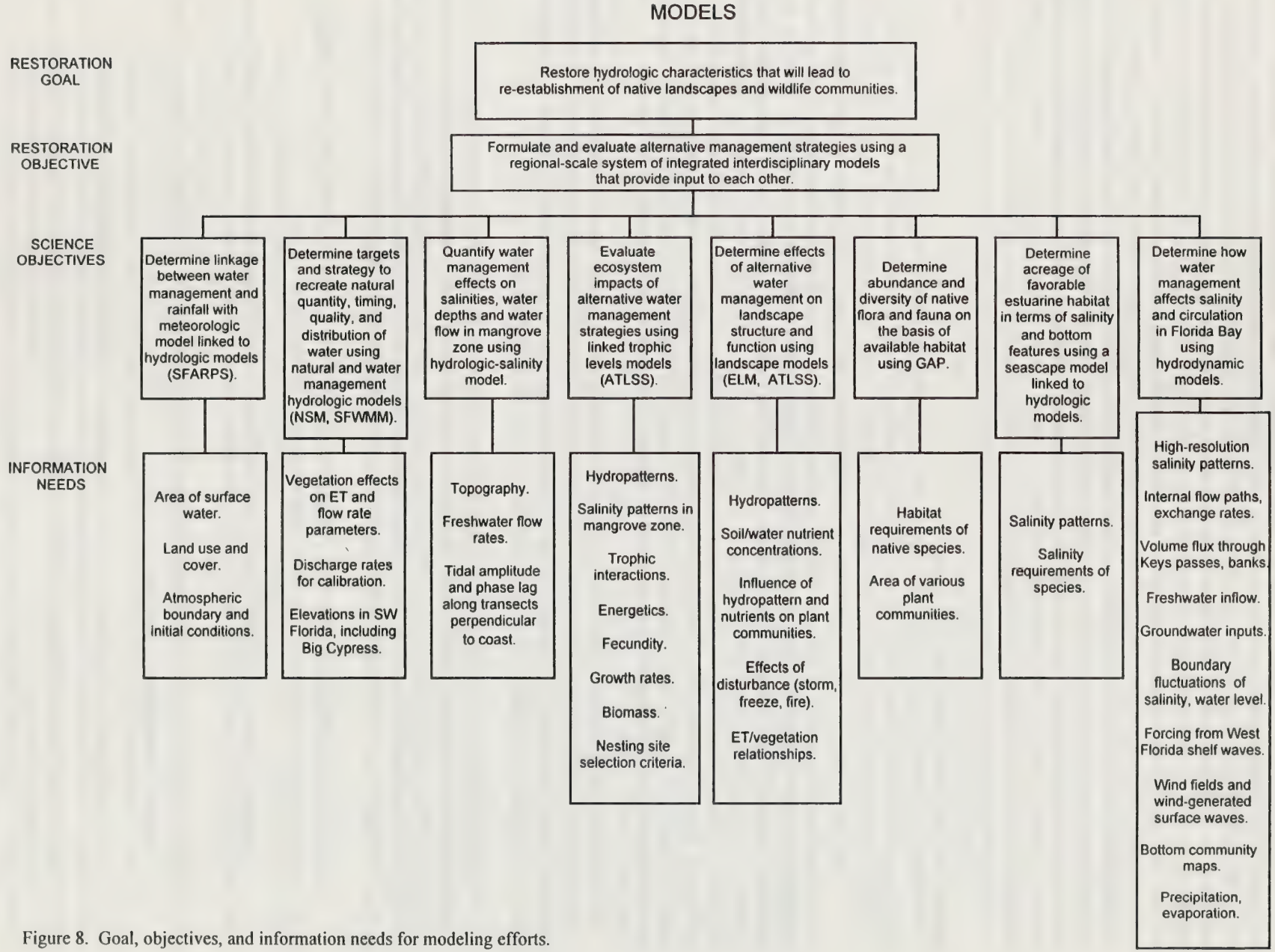

RESTORATION GOAL
Restore hydrologic characteristics that will lead to re-establishment of native landscapes and wildlife communities.
RESTORATION OBJECTIVE
Formulate and evaluate alternative management strategies using a regional-scale system of integrated interdisciplinary models that provide input to each other.
SCIENCE OBJECTIVES
Determine linkage between water management and rainfall with meteorologic model linked to hydrologic models (SFARPS).
Determine targets and strategy to recreate natural quantity, timing, quality, and distribution of water using natural and water management hydrologic models (NSM, SFWMM).
Quantify water management effects on salinities, water depths and water flow in mangrove zone using hydrologic-salinity model.
Evaluate ecosystem impacts of alternative water management strategies using linked trophic levels models (ATLSS).
Determine effects of alternative water management on landscape structure and function using landscape models (ELM, ATLSS).
Determine abundance and diversity of native flora and fauna on the basis of available habitat using GAP.
Determine acreage of favorable estuarine habitat in terms of salinity and bottom features using a seascape model linked to hydrologic models.
Determine how water management affects salinity and circulation in Florida Bay using hydrodynamic models.
INFORMATION NEEDS
Area of surface water.
Land use and cover.
Atmospheric boundary and initial conditions.
Vegetation effects on ET and flow rate parameters.
Discharge rates for calibration.
Elevations in SW Florida, including Big Cypress.
Topography.
Freshwater flow rates.
Tidal amplitude and phase lag along transects perpendicular to coast.
Hydropatterns.
Salinity patterns in mangrove zone.
Trophic interactions.
Energetics.
Fecundity.
Growth rates.
Biomass.
Nesting site selection criteria.
Hydropatterns.
Soil/water nutrient concentrations.
Influence of hydropattern and nutrients on plant communities.
Effects of disturbance (storm, freeze, fire).
ET/vegetation relationships.
Habitat requirements of native species.
Area of various plant communities.
Salinity patterns.
Salinity requirements of species.
High-resolution salinity patterns.
Internal flow paths, exchange rates.
Volume flux through Keys passes, banks.
Freshwater inflow.
Groundwater inputs.
Boundary fluctuations of salinity, water level.
Forcing from West Florida shelf waves.
Wind fields and wind-generated surface waves.
Bottom community maps.
Precipitation, evaporation.

Figure 8. Goal, objectives, and information needs for modeling efforts.

Ecologic models, including landscape, population, and individual-based species models, when supplied with the output of hydrologic models, make the hydrologic information more meaningful in terms of assessing ecological effects. Because the landscape influences water flow and at the same time is shaped by water, hydrologic and landscape models will eventually be linked to allow two-way interactions. One would then be able to observe not only the influences of water management manipulations on landscape patterns and soil subsidence but also the effect on water flow of long-term biological processes such as soil building and landscape pattern formation. Individual-based species models, which are being applied to the large, wide-ranging predators of the South Florida Ecosystem, can show how hydropatterns (spatial and temporal patterns of surface water) could affect feeding behavior and reproductive success of animals such as the large colonial-nesting wading birds, whose populations have declined dramatically in the past decades. Because their foraging area is so broad and foraging success, which affects nesting success, is closely coupled with hydrologic patterns, modeled trends in abundance and recruitment in these populations will reflect trends in ecosystem function.

MODELING HYDROLOGIC PROCESSES

Background

The C&SF project, authorized by Congress in 1948, is a complex system that manages surface and groundwater resources to serve a variety of interests, primarily flood control and water conservation. There has been increasing concern over South Florida's continued rapid population growth and the effects of structural and operational changes in the hydrologic system as related to land-use changes and increased water consumption. There is particular concern about the severely stressed ecosystems of Lake Okeechobee, the WCAs, the Big Cypress basin, and ENP, including Florida Bay. The complex nature of both the hydrologic system and the ecosystems it supports has made it difficult to evaluate the effects of changes in structure or operation of the C&SF project and other human activities. The year-to-year variation in rainfall makes it difficult to distinguish the effect of management actions. Models allow the effects of natural variation and management actions to be separated.

Modeling of the South Florida hydrologic system can be used to: 1) gain a better quantitative understanding of hydrologic processes; 2) identify data gaps and scientific needs; 3) evaluate proposed structural and operational changes in water management; 4) guide day-to-day water management operations; and 5) provide a conceptual framework to interpret, extrapolate, and illustrate data from monitoring programs.

The fundamental steps of a hydrologic science plan that will help achieve the stated objectives are: 1) characterize natural hydrologic structure and function and the effect of rainfall variation, 2) assess present-day conditions, 3) formulate specific restoration objectives that consider natural system requirements and societal demands, 4) define success criteria, 5) develop and evaluate alternative strategies for achieving the objectives, 6) implement structural and operational changes, and 7) evaluate implementation consequences using success criteria.

Hydrologic models are critical to most of these steps. Only a hydrologic modeling system, by supplying surface and groundwater flows as well as water depths, can provide the foundation for:

- A quantitative view of what predrainage patterns of water flow and hydroperiod in relation to rainfall might have been.
- Hydrodynamic models to assess effects of freshwater inflows on salinity and circulation in estuaries as well as regional oceanographic processes.
- Water quality and transport models to follow dispersion of nutrients, contaminants, and sediments.
- Meteorologic models to generate rainfall as a function of local surface moisture features as well as large-scale climatic factors.
- Ecologic models of freshwater wetlands and estuaries at various scales in space and time.

Issues

Hydrologic models are needed to address issues concerning water redistribution in time and space, primarily related to water needs and use by agriculture, urban and industrial areas, and natural ecosystems. Some of the major hydrologic issues are:

- South Florida's economic growth and rapidly growing population, with attendant land development and alterations of natural systems, are placing progressively increasing demands upon the limited water resources of the Everglades. Wellfields to supply increasing urban demand are drawing down the aquifer, affecting water supply, and decreasing hydroperiods in nearby wetlands. New wellfields continue to be constructed, especially on the LEC.

- Land-use changes by local governments are allowing development to encroach into wetlands, diminishing both surface and groundwater storage and thereby reducing water supply. Because shallow aquifer systems provide the majority of water in South Florida, anything adversely affecting these aquifers has far-reaching effects.

- Declines of as much as 10.7 m (35 ft) since the 1930s have occurred in the potentiometric surface of the Floridan aquifer between Orlando and Lake Okeechobee. Lowering of the potentiometric surface has reduced groundwater seepage that previously re-emerged as surface water contributions to the Upper Kissimmee River basin chain of lakes, the Kissimmee River, and Lake Okeechobee.

- Management to control flooding of low-lying urban and agricultural areas in wet years has had a devastating effect on water supplies; hydroperiods and hydropatterns in remaining wetlands; and the quantity, timing, and distribution of freshwater flows to estuaries.

- Saltwater intrusion, the inland shift of the freshwater/saltwater interface, has been caused by a general lowering of the water table. Several municipal water supply wells along the coast have been abandoned, and many others are threatened by saltwater contamination. Saltwater intrusion is not only an urban problem but also a problem for natural ecosystems. The landward spread of mangroves along the northern edge of Florida Bay was caused by saltwater intrusion and has been accompanied by a loss of freshwater marsh. Because location of the fresh/salt boundary is a function of the difference between the water table and sea level, sea-level rise, a continuing phenomenon proceeding at a rate of about 3 cm (1.2 in) every 10 years in South Florida, exacerbates the problem of saltwater intrusion and may someday threaten freshwater wetlands as well as aquifer water supplies.

- Drainage, impoundment, and diversion of water has changed the quantity, timing, and distribution of freshwater flow to estuaries. As a result, some estuaries often receive too much fresh water too quickly during the wet season and too little for too long during the dry season. Others, such as Florida Bay, probably receive considerably less fresh water throughout the year than they did under predrainage conditions and now experience hypersaline conditions of much greater severity, duration, and spatial extent than occurred prior to drainage.

Hydrologic models are needed to address important science questions that include:

- How will restoration changes made in the Kissimmee River affect water levels in Lake Okeechobee and the need for regulatory releases to the St. Lucie and Caloosahatchee rivers?
- How will proposed changes in the regulation schedule of Lake Okeechobee affect LEC water supplies and water flow to Florida Bay?
- How has the C&SF Project changed the spatial and temporal pattern of surface water coverage, water depth, and water movement in wetlands?
- How will hydroperiods and hydropatterns in natural areas be affected by various proposed changes in structures or operating procedures?
- How has the C&SF Project changed the volume, timing, and location of freshwater inflow to estuaries?
- How will the quantity and timing of freshwater flow to estuaries be affected by various proposed changes in structures or operating procedures?
- How might planned or anticipated land-use changes impact water supply and the ability to manage water for ecosystem restoration?

- How might changes in on-farm water management practices and changes in the structure and operation of the C&SF system to control subsidence in the EAA affect the volume and timing of water flow to downstream areas from Lake Okeechobee and the EAA?
- How do undeveloped wetlands modulate hydrologic exchanges between protected wetlands in the Everglades and the developed LEC?
- How do undeveloped coastal wetlands modulate hydrologic exchanges between developed coastal areas and estuaries?

Objectives

The objective of modeling hydrologic processes is to develop a system that can be used to modify/redesign and operate the C&SF Project so it can support ecosystem restoration and at the same time still provide the flood control and water supply needs of urban and agricultural areas. This modeling system must:

- Cover the entire South Florida Ecosystem land base.
- Be capable of addressing both short- and long-term management issues for specific areas and for the South Florida region as a whole; i.e., simulate processes at multiple spatial and temporal scales.
- Be capable of predicting impacts of land-use changes on both water supply and natural communities.
- Generate insight on how to modify the structure and operation of the C&SF Project in order to foster a return to environmental health of the Everglades, the Big Cypress, and South Florida estuaries.
- Help achieve the overall hydrologic objectives of ecological restoration (as stated in SSG 1993) to: restore sheetflow; restore strong hydrologic linkages between areas; eliminate or reduce barriers; restore the dynamic water storage capacity of the system; restore the natural fundamental relationships of surface and groundwater levels and water flow with rainfall; restore more natural quantity, timing, location, and quality of freshwater flow throughout the system and into estuaries; and prevent point- and nonpoint-source airborne or waterborne pollution, including contaminants, excessive nutrients, sediments, and thermal pollutants.

Current Modeling Activities

Several hydrologic models are already in use in the South Florida Restoration effort. Following is a summary of current hydrologic modeling activities and plans of Federal and State agencies. Partly because of the time that has evolved since the draft and final versions of this report and the communication the draft engendered, most of these efforts are already integrated with the approach and recommendations presented later in this chapter.

U.S. Army Corps of Engineers

Traditionally the COE has studied and built projects to solve specific problems. Funding has been limited to a very focused study area and the authorization limited the project scope. In large basins with several watersheds, changing one of the sub-watersheds for flood control can impact functions in other sub-watersheds; i.e., groundwater flow, water supply or even the timing of natural runoff. Faster computers, automated data gathering, and geographic displays have made it possible to include project designs for the larger ecosystems and test for unexpected impacts.

A Hydrologic Modeling Group has been established in the Hydrology and Hydraulics Branch of the Jacksonville District. Its responsibilities are to: 1) develop and maintain hydrologic models, such as surface runoff (precipitation/ground interaction) models, water quality (hydrodynamic) models, groundwater models with surface/groundwater interactions, and GIS; 2) maintain and build data banks for storage of GIS input and output data, such as physical basin characteristics, precipitation, discharge, and other data/information needed in hydrologic models; 3) coordinate with other COE Districts and State agencies that have GIS systems for exchange of data and applications; 4) provide hydrological modeling capability for all COE projects; 5) seek new programming applications and modeling techniques; 6) disseminate new information to users; 7) and assist in training others in the use of large-basin models. The HMG currently includes a staff of four hydraulic engineers. Interdisciplinary specialists in such fields as water quality and environmental, geotechnical, and sanitary engineering should work closely with the modelers.

South Florida Water Management District

The primary hydrologic model used in South Florida has been the South Florida Water Management Model developed by the SFWMD. This model has been useful because it has a relatively broad areal coverage, is grid based, and integrates surface and groundwater systems. Because it is grid based, the SFWMM can simulate spatially explicit water coverage and water depths. This allows hydropatterns to be mapped from SFWMM output.

The Natural System Model, a corollary of SFWMM, represents the system in the absence of canals and other water control structures. Comparison of output from the two models provides perspective on characteristics of the natural hydrologic system in contrast to those of the present system. Because the NSM is executed with the same time series of rainfall data used in the SFWMM, it shows, without the confounding effect of different rainfall patterns, how the structures and their operation have modified system function. This has been invaluable to ecologists in translating rainfall patterns into hydrologic conditions that supported plant communities and wildlife as they might have done in the predrainage system. Because of the lack of pre-1900 rainfall, stage, or runoff data, the NSM provides the only objective, quantitative perspective on hydroperiods, hydropatterns, and water flows in South Florida in relation to rainfall in the absence of canals and other water control structures.

The SFWMM and its NSM corollary simulate flows and water levels (both ground and surface) for an area that includes the WCAs, EAA, much of BCNP, ENP, and LEC. The model provides differing levels of input or simulation sophistication for all the important processes affecting water management in this area: rainfall; ET; infiltration; canal/aquifer interactions; levee seepage; and overland, canal, and groundwater flows.

SFWMD is now developing a new South Florida Regional Simulation Model, a completely redesigned version of the existing SFWMM with capability to simulate the natural system without water management facilities. It will be designed to analyze future regional water management alternatives more efficiently. The SFRSM will take advantage of new databases and recent advances in computer technology, in particular GIS and object-oriented model development. It will use more realistic, accurate, and efficient numerical algorithms that were not implemented during SFWMM development due to resource limitations and lack of data.

Development of SFRSM will be a 3-year collaborative project for a team of SFWMD staff and two contractors. Several Federal and local agencies that will be end users of the model (e.g., USGS, COE, ENP, Dade County) will be involved in planning workshops to define model specifications. To establish and maintain needed inhouse expertise in regional model development and application, SFWMD staff will direct and coordinate all model development activities and perform most of the development. Several Federal agencies will also provide funding and technical expertise to the effort.

U.S. Geological Survey

The USGS Hydrologic Modeling Work Plan covers improvement of algorithms and parameters for major flow pathways in hydrologic models, measurements to supply gaps in needed data for model calibration and validation, and development of spatial databases and digital maps to support modeling.

USGS hydrologic modeling objectives are to: 1) review and evaluate algorithms that comprise the SFWMD's existing regional models and perform error and sensitivity analyses; 2) improve parameters concerning aquifer characterization (e.g., permeability), ET, vegetative resistance to flow, and land elevation; 3) construct and test a framework of computer codes for integrating numerical models of hydrologic and hydrodynamic processes such as overland, channel, and groundwater flows and transport and also improve methods for simulating the nonlinear dynamics of fluid-driven mass and constituents in connected canal/wetland systems (develop a coupled mathematical/numerical model); 4) measure and model groundwater flow from WCA 3B under the protective levee; and 5) prepare a hydrologic/transport model of the mangrove zone.

Measurement efforts will cover surface freshwater discharge to the East Coast, surface and groundwater discharge to Florida Bay, and surface freshwater discharge to the Southwest Coast. Many canal and creek flows to Florida Bay and the Southwest Coast are not presently measured. Stage data are recorded for the East Coast canals, but calibrations to relate discharge to stage data are erroneous and need to be redone.

The USGS is planning an intensive effort in the mangrove zone to support the hydrologic and transport model. In addition to flow measurements already underway in creeks emptying into northern Florida Bay embayments, this includes topographic surveys of the mangrove zone, and paleoecological studies of topographic features (e.g., Buttonwood Embankment).

Spatial database development will include preparation of digital orthophoto maps that show landcover features and vertically fine-scale topographic measurements for input to hydrologic models.

USGS is developing an FGDC-compliant metadatabase and update tool that is customized for the South Florida Ecosystem Restoration effort. The metadatabase will include information about USGS spatial data, both historical and current, that is relevant to the restoration effort. The USGS Distributed Spatial Data Library for South Florida also will cover spatial data of the FDEP and SFWMD. USGS will develop a tool that allows users to search the metadatabase. Much of the USGS spatial data described in the metadatabase will be made available through the Internet. USGS maintains a World Wide Web site that describes South Florida Ecosystem projects, provides access to reports and other products resulting from these projects, and provides links to other Web sites with information relevant to the South Florida Ecosystem.

National Park Service

"Numerical Modeling Studies" is an ongoing project that focuses on development and application of hydrologic models to improve understanding of the principal processes operating in the Everglades. Existing models, particularly the SFWMM and NSM, are being used to help evaluate proposed structural and operational changes in the canal system. Model output produced by simulating proposed alternative strategies are processed, evaluated, and documented specifically with regard to effects on hydroperiods and hydropatterns in the natural areas of ENP. These interpretations are then used by ecologists to evaluate impacts on the ecosystem. In order to enhance reliability of the current models, particularly in wetlands, the Park's hydrologist and modeler are engaged in evaluation of algorithms and datasets associated with the models. Several of their suggestions and products have already enhanced current models.

Future products expected from ENP water resources staff relate to the Experimental Water Delivery Program, Modified Water Deliveries project, and C-111 General Re-evaluation Report. A higher level of effort by the Park hydrology staff will be needed to evaluate impacts of alternative strategies on wetlands for the restoration effort and to provide the support to improve wetland-related algorithms and datasets. Improved rainfall/runoff formulas developed by ENP's cooperators to return the wetlands to a more natural condition and revised operational schemes to improve freshwater deliveries to Florida Bay will require extensive evaluation before implementation. Wetland modeling will be heavily used in these analyses and will require additional support.

National Oceanic and Atmospheric Administration

The National Marine Fisheries Service and National Ocean Service are participating in hydrologic model planning and evaluation activities to ensure that modeling needs with respect to freshwater outflow to estuaries, particularly Florida Bay, will be addressed in future model upgrades and replacements and in data collection to support modeling. These needs are not adequately being addressed by existing models, although the 1993 SSG report suggested a procedure for analyzing certain "freshwater outflow indicator" output of existing models for use in environmental assessment of estuarine impacts of proposed structural and operational changes in the C&SF Project. The suggested procedure uses outputs from the existing SFWMM and NSM. NOAA/NMFS proposes to work with other Federal agencies and the SFWMD to develop and implement analyses and environmental assessment procedures for simulation data that can be used as an index of freshwater flow to Florida Bay and Biscayne Bay. Results could be used to develop operational guidelines and evaluate alternative strategies proposed to improve estuarine conditions. Participation by NOAA/NMFS in model development planning activities and the proposed analysis will help interface hydrologic models with hydrodynamic models for Florida and Biscayne bays and increase the potential that the restoration effort will improve conditions in estuaries.

Approach and Scope

The hydrologic modeling system should be regional in scope so changes made in one area can reveal resulting changes in other areas. At the same time, the system should provide the resolution required to address questions about localized changes and effects. At a minimum the system should consist of regional models and models at a smaller temporal and spatial scale. The models should be capable of being linked and interfaced using compatible formats for input and output. The main technical concerns of this effort are the large geographic area under consideration, massive amount of data that will be collected, and effort needed to efficiently organize the data.

The proposed approach is to develop a hydrologic modeling system using existing models as its foundation. Spatially explicit hydrologic models, rather than "pot" models, are necessary because hydroperiod (duration of continuous water coverage) and hydropattern (where and when the water coverage occurs) are thought to affect vegetation coverage and the support value of wetlands for wildlife.

SFWMM and NSM are useful in combination for interpreting hydrologic output in an ecological context. The SFWMM should be a fundamental component of the hydrologic modeling system, and updates of SFWMM should include an NSM version. Other existing models should be evaluated for incorporation into the modeling system to meet various needs. The SFWMD has identified 45 existing hydrological models and 26 models under development for use in South Florida. Some are different applications of the same model; some are models of detailed temporal and spatial resolution such as MOD-FLOW, MODBRANCH, DWOPR, HEC-2, UNET, and CHANOP. These models are being applied to specific problems such as wellfield analysis, pumping sizing, and seepage studies.

The hydrologic modeling effort will have three parallel tracks: 1) model improvement, 2) model development, and 3) model application.

- **Model improvement**

Improvements in existing modeling capability are necessary to adequately support a scientifically based restoration program and provide useful input to other types of models. Improvements to correct shortcomings in the SFWMM should be a major priority. Planned upgrading will be accomplished with improved algorithms, parameters, input data, modular codes, and pre- and postprocessing capabilities. Process studies and measurements are needed to improve algorithms and parameters (e.g., ET, flow resistance, levee leakage, and seepage of groundwater into canals) in existing hydrologic models. It is important to rewrite the SFWMM code to make it both easier to follow and more flexible. New code should be developed to make it possible to test water management alternatives, including the natural system alternative, by changing structural and operational parameters in an input data file rather than having to change program code. Graphical interfaces that provide preprocessing and postprocessing capability and make it easy to summarize and analyze input and output also will be constructed. Initial integration of hydrologic models will be accomplished simply by standardizing input and output data parameters and formats. Some of these improvements are already underway.

- **Model development**

Concurrent with improving existing models, models must be developed for several areas not yet covered by adequate hydrologic models. Spatially explicit models that include both surface and groundwater should be included in model upgrading and development; these do not presently exist for Southwest Florida. Spatially explicit models such as grid-based models, in addition to providing water flows, provide a grid of water depths that can be used to obtain hydroperiods and hydropatterns that relate to ecologic structure and function. Models must be modified or developed to extend to the coasts and simulate freshwater outflows to estuaries. Existing models do not have the topographic detail needed to adequately model these outflows, and special effort is needed to obtain more detailed near-coast topographic data. This is particularly important for determining how to establish more natural timing and volume of freshwater flow to Florida Bay.

Natural system versions of grid-based or otherwise spatially explicit models should be included in all hydrologic model upgrades and replacements so the most current model of the present system always has a natural

system corollary. As water management models are improved with new algorithms, parameters, and data, the ability of the natural system corollaries to simulate the predrainage system can be expected to also improve.

Monitoring provides baseline data and data to assess responses to operational changes and is critical for model testing and refinement. Parallel with model development, the current monitoring network should be upgraded to improve present flow estimates and expanded to cover areas not presently covered, such as surface flows to Florida Bay and Southwest Coast estuaries. Groundwater flows to Florida Bay also need to be determined.

In addition, more advanced and comprehensive models should be developed that will use new programming languages, such as object-oriented programming, and support systems with greater capability than those used in present models. The SFRSM being developed by SFWMD (discussed above) is one example.

The iterative process must be a significant component of hydrologic model development. Basic to simulation modeling is quantification of values for each variable in the model. Quantification requires either empirical data or sets of assumptions based upon fundamental knowledge of each variable's functions. Development of preliminary prototype simulations help to identify and organize essential data. As understanding of variable functions and interactions improve, reiterations of the simulations contribute to improved knowledge on the hierarchical, temporal, and spatial aspects of each modeled variable.

The modeling system should be based on GIS technology and use a GIS input and output shell to provide linkages between the different databases and models, help interpret simulation results in a spatial context, and make the system user friendly. GIS technology allows generation of new spatial data through comparison and analysis of multiple spatial themes. To accomplish this creation of new data, most GIS systems share a conceptual model that differentiates spatial elements into layers or themes, such as vegetative cover, soil types, land-use zones, and slope types. These themes are represented in various formats, such as arcs/nodes, polygons, grid cells, and triangulated networks. A GIS organizes information about both spatial location and value of each unit in a data layer, so that new data can easily be derived when two or more layers are compared. A GIS allows storage, manipulation, and analysis of large volumes of cartographic data that would be cumbersome using conventional methods and facilitates an easily updated resource database. A GIS can be used to import and couple input data to models, provide graphical display, and develop land-use, soil-group, and sub-basin boundary maps.

- **Model application**

The hydrologic modeling system will be used by Federal, State, and local agencies involved in various aspects of land and water management in South Florida. To ensure successful application, a central repository for the system is needed, access must be provided to all agencies involved in the restoration effort, and the models must be integrated in a manner that minimizes the effort required for application and interpretation.

Hardware and software systems must be designed to be compatible with existing systems used by the SFWMD, NPS, USGS, COE, EPA, NOAA, and other agencies involved in restoration activities. The system should be designed to run on microcomputers or workstations. Most GIS software can reside on current and anticipated new generation microprocessor workstations. UNIX-based workstations with powerful graphics capabilities facilitate linkage of models, development of user-model interfaces, and development of highly versatile graphical output options. The proposed GIS will provide a means to accomplish some of the interfacing. Modeling outputs should be formatted in standard formats for postprocessing into standard database and GIS utilities.

Executive Order 12906 (April 1994) mandates that Federal agencies document new geospatial data beginning in January 1995 and make this documentation (metadata) available to the public through a National Geospatial Data Clearinghouse. The Executive Order requires that the metadata conform to the FGDC Content Standards for Digital Geospatial Metadata. One repository for South Florida spatial data will be the Florida GIS DSDL being developed by the USGS. This effort covers all USGS and State spatial databases that are relevant to the South Florida Ecosystem Restoration effort. Standard postprocessed spatial information products will be archived in the USGS GIS repository, which is designed to accept multi-GIS databases and will be accessible through ARCINFO, GRASS, and other GIS software. Other agencies (e.g., NOAA, COE) also are building spatial metadata and centralized spatial database libraries for South Florida.

Extensive interagency cooperation and coordination is critical to successfully develop and operate the hydrologic models. Development of the system will provide a framework for interagency exchange and integration of ideas, data, and modeling efforts. The assembly of improved knowledge and interchange of objective analytical concepts and techniques among hydrologic researchers, resource managers, and development regulators can be expected to significantly improve system management procedures and technical coordination among agencies with management and regulatory responsibilities in the South Florida Ecosystem.

Information Needs and Recommendations

▸ Modify, enhance, and apply the SFWMM and NSM.

Several modifications and enhancements should be made to the SFWMM to improve and extend its performance and utility. A two-step approach is recommended. First, the existing SFWMM should be improved to allow for its relatively immediate use in water quantity decision making. Second, and concurrent with the modification, major enhancements to the SFWMM are proposed. Once completed, most water quantity issues for the freshwater system could be answered within a single modeling framework. Important information needs for improvement of the SFWMM are:

- Estimates of evapotranspiration. ET is a major pathway for water leaving the system. ET may vary spatially as well as temporarily because of vegetation and microclimate variation. ET has been poorly studied considering its importance to the overall water budget.
- Estimates of groundwater flow and levee seepage losses from the WCAs. These losses are significant but poorly quantified. Seepage losses through and under levees range from 4 to over 100 cfs/ft head/mile of levee. The higher seepage losses occur along the exterior levees bordering WCA 3B, where the levee coincides with a highly permeable segment of the Biscayne Aquifer.
- Estimates of seepage losses through salinity control structures. Seepage loss rates are estimated to range from 2 cfs/ft head/mile in the northern areas to 5 cfs/ft head/mile in the southern areas.
- Estimates of surface freshwater discharge to the East Coast. This is poorly estimated for 19 of the 25 canals discharging to the East Coast. Data collection and analysis are needed to properly calibrate flow rates to stage in the other canals. Recalibration may allow historic discharge time series to be reconstructed from historic stage data.
- Estimates of both surface and groundwater flows to Florida Bay.
- Quantification of surface freshwater discharge to the Lower West Coast. Many of the canals discharging fresh water to the Southwest Coast are not calibrated or monitored.

▸ Develop and apply groundwater-wetland models.

Development of fine-resolution groundwater-wetland models is needed to address site-specific questions in several subregions whose hydrologic regimes are dominated by wetland-groundwater interchanges (e.g., the WCAs, EAA, LEC wellfields). These models will answer local questions, such as effects of large-scale groundwater pumping or lowered water tables within Dade County on the hydrology of the C-111 basin and detailed distribution of flows delivered to the Loxahatchee NWR and ENP, as well as distribution of flows within the EAA. The need to evaluate salinity intrusion within the Biscayne Aquifer will also require more detailed groundwater modeling capabilities than those proposed for the SFWMM.

Groundwater model development will require extensive field data collection to establish a more definitive database on subsurface stratigraphy and transmissivities, particularly in the vicinity of canals. Applications of models developed will center on evaluation of effects of operational water delivery changes on coastal salinity intrusion, effects of large wellfields being developed in Dade County, and connections between groundwater and major wetlands.

▸ Prepare software for routine calculation of water budgets from model input and output.

A water budget for the South Florida hydrologic system is essential to identify major sources and sinks of water, determine locations where inadequate data exist, and provide a fairly concise estimate of the actual magnitude

of water available in the system. The modeling system should be capable of generating a water budget that shows the magnitude of inflows and outflows for the Region as a whole as well as subregions. It should be possible to model the effect on the water budget of proposed modifications in C&SF Project structures or operations. Comparison of water budgets for the natural and current systems would provide insight on the effect of anthropogenic influences. The capability to routinely produce water budgets should be a basic feature of the summarizing and integrating software.

▸ Develop hydrologic-hydrodynamic models of the mangrove zone.

Physical models of the mangrove zone should be constructed to provide water depths and salinities as dynamic functions of freshwater inflow from upstream and tidal and nontidal forces influencing sea level. Such models can be used to drive forage fish and wading bird models to provide insight on how natural and anthropogenic changes in freshwater inflow affect recruitment to offshore fisheries and colony site selection and fledgling production by wading birds. Mangrove zone hydrologic-hydrodynamic models that simulate freshwater flow to Florida Bay and the Lower Southwest Coast are critical to development and operation of hydrodynamic models of Florida Bay and adjacent areas of the coast. Topographic information must be collected in order to operate the hydrologic-hydrodynamic models. Several models (or several separately calibrated versions of the same model) will be necessary because of morphogeologic and tidal differences along different segments of the coast.

▸ Develop interfaces to link hydrologic models to other models.

To provide effective support for ecosystem restoration, hydrologic models must be linked to other types of models. Hydrologic input is needed for hydrodynamic, meteorological, landscape, ecologic, and water quality models. Two-way linkages between these and hydrologic models will make simulations even more realistic by incorporating interdependencies and feedbacks.

▸ Develop and apply dynamic routing and watershed runoff models for inflows to Lake Okeechobee.

Dynamic river-routing and field-level watershed runoff modeling capabilities are needed for the Kissimmee River system, Fisheating Creek, Taylor Creek, and Nubbins Slough. A Kissimmee River model is particularly needed because the restoration project in progress in the river basin may affect water levels in Lake Okeechobee.

▸ Integrate modeling components.

Hydrologic models must be integrated in a manner that minimizes the effort required for application and interpretation. This integration requires development and coupling of four types of interfaces:

- Model-user interface is the actual environment through which the user accesses various programs, selects program attributes, inputs data, simulates various conditions, and evaluates model output.
- Model-model interface, which is transparent to the user, includes the essential linkages between various models and their outputs.
- Input data-model interface is necessary to couple large databases with models and allow efficient retrieval of data based on user-selected conditions.
- Output data-graphical/visualization interface is critical to presentation of voluminous simulation results in a form interpretable by decision makers, as well as scientists and engineers.

Beyond these interfaces, large but separate databases must be compiled and made readily accessible for common use. Analogously, models being developed or adapted within this proposed plan must be compiled and integrated through the above interfaces.

▸ Maintain system components.

The investment represented by the models, tools, and databases proposed for development will be large. For their effective use over the length of the study and the long term, the technology must be appropriately maintained. Maintenance is much more than providing locations for data and models to reside. It also must include

the necessary modifications related to error identification, fulfilling additional requirements as they arise, and the opportunity to benefit from improved technology. Furthermore, hardware and communications systems must be maintained to allow users to access models and data from remote entry locations.

- Transfer technological information.

This includes distribution of reports, user manuals, model user support, etc. Additionally, it might include publishing periodic newsletters or information bulletins reporting new available technologies, updates to existing models, errors found in existing models, etc., and responding to requests for various models and databases.

- Facilitate application of models.

Access to the modeling system for all agencies and groups with responsibilities for managing hydrology in South Florida must be ensured.

- Form a central repository for hydrologic databases and models, with responsibility for model integration, maintenance, and application and for technology transfer.

A single group or organization should be responsible for the Federal role in coordinating integration, maintenance, and application of hydrologic models. The office should be located in Florida and act as a technology center in support of the consortium of agencies involved with management of the South Florida hydrologic ecosystem. This office would appropriately be the primary distributor of technological information for model use. To support users and maintain the system, the group should become proficient appliers of the models. These applications might be on a cost-reimbursable basis, with reimbursement coming from the agency requesting the application. The COE should be the central Federal agency to testify and administer funding for the hydrologic modeling effort.

MODELING HYDRODYNAMIC PROCESSES

Background

Hydrodynamic modeling is needed to simulate salinity patterns and circulation processes within Florida Bay as a function of freshwater inflow, local precipitation, wind, temperature, and regional circulation processes. Other South Florida estuaries also have similar needs for hydrodynamic modeling.

Issues

A system of hydrodynamic models will address issues related to potential changes in Florida Bay resulting from modifications in the C&SF Project. The models will address important science questions that include:

- What are the patterns of salinity and circulation in Florida Bay in relation to freshwater inflow?
- How does water from Shark Slough affect salinity, circulation, and nutrient dynamics in Florida Bay?
- What are the major factors influencing circulation in Florida Bay?
- What are the oceanic contributions of nutrients to Florida Bay relative to the terrestrial contributions?
- How are algal blooms in Florida Bay influenced by circulation?
- What is the turnover time of water in Florida Bay and how does it differ by region of the bay?
- How has the Overseas Highway affected the circulation of Florida Bay?

Objectives

The objective of hydrodynamic modeling is to develop a system of circulation models to predict circulation, mixing, and salinity patterns in Florida Bay as a function of freshwater inflow and other variables. This modeling system must:

- Be capable of resolving the influence of density-dependent forcing.
- Include a regional circulation model that can provide boundary conditions for the Florida Bay model.
- Include a salt-budget model for Florida Bay.

Current Modeling Activities

National Park Service

A workshop on Florida Bay hydrodynamics, sponsored by the NPS and organized by the Florida Institute of Oceanography, in cooperation with NOAA, was held in October 1993. Subsequently, the NPS funded four exploratory modeling studies to show the usefulness of different approaches and better identify data needs required to support hydrodynamic modeling: 1) time-dependent, Blumberg-Mellor-type three-dimensional model (Galperin et al. 1995); 2) two-dimensional nearly horizontal flow finite element model (Wang 1995); 3) mass balance model (Fourqurean et al. 1995); and 4) curvilinear-grid three-dimensional circulation model (Sheng et al. 1995a,b). These modeling efforts indicated the importance of improving the spatial information database on freshwater inflow to Florida Bay, precipitation over Florida Bay, evaporation, wind, salinity, tidal phase and amplitude, and current velocity. Wang (1995) emphasized the need for fine-scale (both temporally and spatially) salinity data. Wang also said that detailed horizontal modeling capability was needed to adequately model the dynamics of Florida Bay because of the complex topography and shallowness of the Bay.

U.S. Army Corps of Engineers

The COE Jacksonville District is planning to have the COE Waterways Experiment Laboratory in Vicksburg, Mississippi, develop circulation dynamic models for Florida Bay and Biscayne Bay. Both models will be two-dimensional finite element models that employ vertically averaged, shallow-water equations capable of resolving the influence of the partially submerged mudbanks, mangrove swamps, and coastal boundaries. The models, adapted from an existing hydrodynamic model, are being modified to incorporate the capability to simulate density forcing caused by strong horizontal salinity gradients. Each model will have an unstructured computational grid that can be locally refined in the vicinity of small-scale flow features and resolve important small-scale details.

Florida Bay Program Management Committee

The Florida Bay Program Management Committee commissioned an expert panel to review the four modeling reports funded by the NPS and the work statement for the model planned by the COE. Following this review, a workshop was conducted in which the expert panel participated.

National Oceanic and Atmospheric Administration

The NOAA Florida Bay Program is funding a project by NOAA/NOS and Princeton University to quantify the degree to which Florida Bay is physically coupled to its surrounding coastal and oceanic environments and to simulate boundary conditions (sea-surface elevation, potential temperature, salinity, and velocities) for hydrodynamic models. The modeling group will provide the boundary condition information by extending the currently operational East Coast Forecast System to the Gulf of Mexico using the Princeton Ocean Model (Blumberg and Mellor 1987; Mellor 1992). The goal is to determine how open ocean forcing from the Gulf model can be incorporated into a model of Florida Bay and to address the bay's interaction and exchange with the adjacent shelf and Gulf of Mexico. The horizontal resolution of the Gulf model is about 15 km (9 mi). If it is determined this scale is too large to provide information to Florida Bay models, then the group will embed a higher-resolution South Florida regional model into the Gulf model.

Approach and Scope

Florida and Biscayne Bay modeling must incorporate horizontal detail to take into account important small-scale features (e.g., channels and passes) that influence exchange and circulation. The scope of the hydrodynamic modeling program must extend beyond the boundaries of Florida Bay to include processes influencing conditions along the boundaries of the bay. Major boundaries are the open Gulf of Mexico; the Florida Keys islands, passes,

and bordering Atlantic Ocean; and mainland Florida with its contributing freshwater inflow. The mangrove zones of both Florida Bay and Biscayne Bay should be covered by hydrologic/hydrodynamic models that link upstream hydrologic models to estuarine hydrodynamic models. Hydrodynamic models should be capable of supporting water quality models and ecosystem models.

Information Needs and Recommendations

- Spatially and temporally detailed data on salinity, tide, and currents in Florida Bay and adjacent areas and Biscayne Bay.

- Data on the influence on Florida Bay of circulation patterns in adjacent waters.

- Estimates of freshwater inflows to Florida Bay as functions of rainfall in the watershed under predrainage and present (modified watershed) conditions.

- Detailed topographic information on the mangrove zone along the north edge of Florida Bay and measurements of surface and groundwater flows to Florida Bay.

- Estimates of direct precipitation over Florida Bay.

- Estimates of evaporation from Florida Bay.

- Boundary conditions along the western margin of the bay and in the Keys channels.

- Updated bottom topography of Florida Bay.

- Station elevations (relative to geodetic vertical control points) for existing ENP continuous monitoring stations within the mangrove zone and in Florida Bay.

- Further development and refinement of the hydrodynamic models to allow them to support water quality models and ecosystem models.

- Technical reviews of the hydrodynamic models at critical development stages by experts on Florida Bay and South Florida estuarine and coastal systems.

MODELING METEOROLOGIC PROCESSES

Background

Rainfall is the major source of fresh water to South Florida. During the rainy season (May-October) easterly waves, cold lows, depressions, and other tropical weather disturbances contribute about 50% of the annual precipitation. The remainder of wet-season rainfall (roughly one-third of the annual total) is from daily thunderstorms associated with convergence generated by sea breezes from the east and west coasts (Burpee 1979; Burpee and Lahiff 1984; Woodley et al. 1982). Dry-season rainfall associated with frontal passages supplies less than 20% of the annual precipitation. Hence understanding of tropical weather disturbances, coastal sea breezes, and their interactions are critical to modeling and predicting behavior of the atmosphere over South Florida.

The many changes in wetland area and land use in South Florida in the past century may have affected rainfall. Soil moisture, vegetative cover, surface roughness, and albedo influence stability of the overlying atmosphere and development of the sea-breeze convergence zone and its resulting thunderstorm complexes. The area of surface water and extent of soil moisture influence ET, which feeds convective rainfall. Replacement of vegetated surfaces with paved surfaces affects albedo and the vertical temperature gradient, which drives convection. The natural system hydrologic model of Fennema et al. (1994) suggests that a considerably larger area of surface water covered South Florida for a longer part of the year in the predrainage system than today. Satellite imagery of South

Florida reveals that extensive areas once vegetated now are covered with concrete or asphalt, creating an "urban heat island effect" that enhances local convection and localizes rainfall. It is important to quantify changes in rainfall patterns that might have occurred due to these alterations.

Hydrodynamic models of Florida Bay are being developed to show how changes in freshwater inflow affect bay salinity patterns, turbidity patterns, and circulation. These models will depend heavily on estimates of freshwater inflow, direct precipitation over Florida Bay, and wind fields. Hydrologic models will be the major source of information on freshwater inflows to the bay. Meteorologic models, by contributing more accurate precipitation data to hydrologic models and providing precipitation and wind stress fields for Florida Bay, can ensure better performance from the hydrodynamic models. High winds create surface stress over the water that causes waves to form and results in sediment resuspension and turbidity. Therefore wind data are needed as input to a wave model and sediment resuspension and transport models.

Rainfall is an important input variable to hydrologic and hydrodynamic models but is so variable spatially that it is not adequately represented by data from existing monitoring stations. Coverage is particularly poor for large estuarine water areas such as Florida Bay. A dense spatial grid of rainfall data for South Florida, including Florida Bay, is now being produced by NOAA's NEXRAD radar system. Accumulated 6-hr precipitation estimates for a dense spatial grid are available from NEXRAD and are being recorded and archived, however the error in these data can be considerable. A meteorologic model is needed to help correct these errors so that reliable, spatially dense rainfall data can serve as input to hydrologic models of the South Florida land area and hydrodynamic models of Florida and Biscayne Bays.

Episodic meteorologic events are major forces that affect ecosystem structure in South Florida. These short-term events have long-term consequences on vegetation patterns and topography and, through these, on water flows and hydropatterns. Ecologists have requested reconstructions of wind and precipitation fields associated with major hurricanes and storms to help them interpret landscape patterns and understand the changes caused by these events.

Issues

Major meteorologic issues are of two types: 1) those recognized by environmental managers and citizens and 2) other very important issues that concern scientists because they handicap their ability to provide the scientific information and tools needed to support an effective restoration.

- South Florida's rainfall is highly variable in both space and time, causing errors in estimates of total rainfall from spot measurements. These errors can affect the accuracy of hydrologic models and their ability to predict stream flows. High resolution quantitative precipitation predictions are not currently available.

- Changes in surface water area, soil moisture, and land cover are known to influence rainfall through their effect on ET, albedo, and the vertical air temperature gradient, but no quantitative determination has been made of the effect on South Florida's rainfall pattern of the C&SF Project and other large-scale hydrologic alterations.

- Water management changes proposed in future restoration strategies need to be evaluated for their potential effect on rainfall patterns.

- Surface wind stress is a dominant force determining circulation, sedimentation, and resuspension in Florida Bay, and surface wind predictions are needed for input to hydrodynamic models of the bay.

- Direct precipitation is a major source of fresh water to Florida Bay but is poorly measured. High-resolution spatial rainfall predictions for the bay are not currently available.

- Improved accuracy and resolution of hydrologic models are important to the restoration effort and also to water managers in handling stormwater runoff following major rainfall events.

- Data on evaporation, an important influence on Florida Bay salinity patterns and circulation, are lacking.

- Long-term changes in vegetation patterns, water flows, and hydropatterns can result from episodic events, but the detailed wind fields needed to interpret landscape patterns is lacking.

- Numerical models in operation at the National Meteorological Center have domains that cover the entire earth (global models) or most of North America (regional models) and have a horizontal resolution too coarse (about 100 km [62 mi] for global models and 50 km [31 mi] for regional models) to adequately represent local atmospheric circulation.

Objectives

The objective of modeling meteorologic processes is to develop a regional model able to:

- Predict wind stress over South Florida, Florida Bay, and adjacent marine areas.
- Predict precipitation over South Florida and Florida Bay as a function of regional weather patterns and local land surface conditions (surface water, soil moisture, and land cover).
- Interact with hydrologic models to predict the effect of past and future water management changes on South Florida's water budget.
- Simulate thunderstorm complexes that form due to sea-breeze convergence.
- Estimate evaporation over Florida Bay.
- Reconstruct wind and precipitation fields associated with episodic meteorologic events such as past hurricanes and other major storms.
- Provide the atmospheric component of a comprehensive coupled hydrologic-hydrodynamic-meteorologic model of South Florida.

Current Modeling Activities

National Oceanic and Atmospheric Administration/University of Miami

A team from the Hurricane Research Division of NOAA's Atlantic Oceanographic and Meteorological Laboratory and the University of Miami, in cooperation with the Miami National Weather Service Forecast Office and SFWMD, is adapting a mesoscale atmospheric model (ARPS, see below) to address South Florida issues. This model, known as SFARPS (South Florida Advanced Regional Prediction System), is scaled to adequately represent the local atmospheric circulation in the South Florida Region.

During the first year, the model code was acquired, appropriate parameters for South Florida were entered, software modifications were made for local computers, an inventory of available surface observations was made, sources of high-resolution land surface data were explored, software was prepared for presenting and evaluating model results, and a workshop was held with local circulation and hydrology modelers and operational meteorologists from the NWS and SFWMD (DeMaria et al. 1994). The purpose of the workshop was to encourage cooperation and interaction; discuss overlapping boundary condition interests, grid geometries, simulation experiments and verification data; and address potential cross-discipline use of the model. Recently a DEC ALPHA Computer Work Station was acquired, which will speed up development time. Current and planned work on this project is presented below.

Approach and Scope

Adaptation of an appropriate existing model was the most effective approach to satisfy the need for a regional meteorologic model of South Florida. Needed was a high-resolution (1- to 10-km grid), nonhydrostatic model able to simulate thunderstorm complexes that form due to convergence of sea breezes from the east and west Florida coasts. With proper boundary conditions, the model should be suitable for predicting heavy rain episodes associated with tropical disturbances and fronts. The model should also be able to supply boundary conditions (precipitation, evaporation, and wind stress) to ocean and bay circulation models and hydrologic models and to accept initial input boundary conditions from the hydrologic model. Linkage of meteorologic and hydrologic modeling is critical to evaluating effects of water management alternatives on the regional water budget.

The model selected was the Advanced Regional Prediction System (ARPS) model developed with National Science Foundation support at the University of Oklahoma's Center for Analysis and Prediction (Droegemeier et al. 1991). In addition to filling the above requirements, this model has the advantages of explicit cloud microphysics (critical for resolving individual thunderstorm complexes), an adaptive grid in which grid points are dynamically redistributed for increased resolution in high-gradient regions, and ease of portability among different computer architectures. The surface evaporation and radiation budgets of the model are highly dependent on land use, vegetation and soil specifications that help determine soil moisture, surface albedo, roughness length, surface heat capacity, fraction of a grid cell covered by vegetation, type of vegetation (because of effects on both albedo and ET), and surface temperature. Since several of these parameters are affected by water management, the model is ideal for use in determining the effect of past and future water management changes on South Florida's water budget. Interaction with scientists at the SFWMD, NPS, and other agencies will be an important step in adapting the model to South Florida.

Adaptation of the ARPS model to South Florida is a multiyear project being conducted by NOAA/AOML and UM in cooperation with the NWS and SFWMD (see above). The next steps for current work are:

1. Obtain data for model test cases, including WSR-57 or WSR-88D radar data for verification. Initialize the model with observed data and evaluate its ability to predict organization of precipitation by comparison with radar data and rain gauge data where available.

2. Acquire high-resolution data sets on actual land use/cover, soil/vegetation, and terrain, and use these data sets to increase the realism of ARPS model simulations.

3. If appropriate, conduct a field experiment using the sophisticated suite of atmospheric and oceanographic sensing equipment aboard the NOAA P3 aircraft to better define initial conditions for a real-time model test and document thunderstorm evolution.

4. Evaluate the model's prediction of surface wind fields by comparison with all available wind observations. Develop and apply techniques (e.g., DeMaria et al. 1992; Powell and Houston 1993) to generate detailed surface wind analyses for input into ocean and bay circulation models. Investigate the possibility of using WSR-88D wind and reflectivity data to initialize and verify the model.

5. Use the model to reconstruct episodic/catastrophic meteorologic events and local weather regimes that critically affected the South Florida Ecosystem (e.g., Hurricane Andrew, Tropical Storm Gordon, Hurricane Donna, the Hurricane of 1935). Archive simulation results and produce a catalog of archived data sets on specific episodic events.

6. Perform a natural system sensitivity test to estimate impact of changing land use and soil conditions on the typical summer sea-breeze thunderstorm development cycle and subsequent rainfall distribution.

7. Collaborate with SFWMD hydrologists to integrate the hydrologic and meteorologic models and write a proposal.

8. Develop the capability to provide corrections for NEXRAD radar data and mesonet observations. As a future design feature of the model, prepare an automatically generated adjoint version for 4-D assimilation of asynoptic NEXRAD radar data and mesonet observations. This capability will be especially useful in predicting, after their initial formation, subsequent development of thunderstorm complexes due to outflow interactions and mergers.

The geographic scope of meteorologic modeling is the Everglades, Florida Keys, Florida Bay, Biscayne Bay, and portions of the Atlantic and Gulf of Mexico basins. The model domain is bounded on the north by Tampa and Melbourne and on the south by the north coast of Cuba. NEXRAD WSR-88D radars, which can be used to help calibrate and validate the model, will be operational near the four corners of the model domain at Miami, Tampa, Melbourne, and eventually Key West.

Information Needs and Recommendations

- Provide supercomputer access. A major problem model developers face is lack of access to a supercomputer. Such access (possibly to the COE supercomputer in Vicksburg) would greatly expedite this work.

- Provide funding and other support to complete meteorologic model development and linkage to hydrologic and hydrodynamic models so the effect on the water budget of past hydrologic changes and future water management alternatives can be evaluated.

MODELING ECOLOGIC PROCESSES

Background

Ecologic models are essential components of the South Florida Ecosystem Restoration initiative. Models that relate species, populations, communities, and landscapes to simulation outputs of hydrologic models are the only objective way to evaluate alternative water management strategies for their influence on landscapes, plant communities, and wildlife. Ecologic models are critical for understanding the connections between hydrologic conditions and ecosystem structure and function. The restoration approach is based on the reasonable premise that hydrologic restoration is the foundation of ecological restoration. Models are essential to determine why this is so, identify key characteristics of the predrainage hydrologic system that maintained predrainage resource abundances, and quantify the relationships between hydrologic variables and indicators of ecosystem health. These models must demonstrate how certain key features of the predrainage Everglades -- large spatial extent, spatial heterogeneity, sheetflow, and dynamic storage -- supported a healthy ecosystem, resilient to perturbations, and supportive of abundant and diverse vegetation and wildlife. A quantitative explanation of the connections between hydrologic function and ecosystem health is needed to strengthen scientific understanding about why these system attributes must be reinstated and to communicate this understanding to managers and the public.

Models are critical to the adaptive management approach that will be employed in the South Florida Ecosystem Restoration effort. The most useful models will be those that help both to understand the connection between ecosystem health and hydrologic function and to assess the effects of proposed management alternatives. For use in assessment, models must be able to simulate selected ecological success measures.

Assessment needs should be given the highest priority in model development. Ecologic assessment models are needed for all phases of the C&SF Project redesign, from the initial justification (reconnaissance) phase through feasibility, field testing, implementation, and monitoring. If based on scientifically credible concepts, simple assessment models, including both diagrams and line graphs, may be useful in some applications. The immediate and long-term need, however, is for models that embody the general structure of the system and simulate ecosystem function. Ecologic models that can respond to output of spatially explicit hydrologic and landscape models and integrate the support functions of a spatially heterogeneous system are essential. Models that can demonstrate why and how the natural hydrologic system supported a greater abundance and diversity of fish and wildlife, cleaner water, and other indicators of ecosystem health will be the most reliable models for testing the benefits of alternative water management structures and operations. Such models may help managers distinguish between changes that occur due to alteration in water management strategy and those that occur for other reasons.

Population trends, plant community succession, and various ecological processes can be simulated under present and predrainage conditions with the same time series of rainfall. Comparisons will then show which aspects of the altered hydrologic regime have had the major effects on the ecosystem and the natural relationship of spatial and temporal patterns of hydrologic conditions with species, communities, and landscapes characteristic of South Florida. Predrainage simulations will provide an ecologically supportable, objectively determined, and relatively unbiased target for restoration efforts.

The predrainage natural system is a good restoration target because it functioned well in supporting landscape patterns; clean and abundant water supplies; and large populations of wading birds, gamefish, and other wildlife that are the objectives of restoration. It is an unbiased target because it does not favor one species or

community over another but rather the ecosystem as a whole. Because of irreversible changes that have occurred with expansion of the modern human population, one cannot expect to totally regain the original species richness and wildlife abundance of the area. However, having a target based on predrainage conditions, as best they can be defined, will ensure that the restoration effort leads to change in the right direction. Simulations from "natural system" executions of hydrologic and ecologic models (Fennema 1992; Fennema et al. 1994) will provide standards against which to test alternative management actions and to measure success, once actions are implemented.

Issues

Strategic ecologic issues that models are needed to address are listed below as questions in the context of system-wide objectives presented by the Science Subgroup (SSG 1993). Answers to these science questions are critical to determine responses of the system to alternative water management options. The questions will be answered not by modeling alone but by modeling in concert with related field studies and experiments, as well as analyses of monitoring data. Investigations are most effective when models and other activities are integrated and modeling activity is initiated at the beginning of the study. The types of models most suitable for addressing each objective and its associated questions are listed below the objective. The variety of models needed to accomplish the tasks of ecosystem restoration is large: landscape models, succession models, biomass models, community models, population models, fate models, biodiversity models, etc. Many questions require a system of linked models. Subregion chapters point out other issues and science questions that modeling must address.

Restore ecosystem structure and function.

Models: Landscape models linked interactively to hydrologic models and incorporating biological and physical processes such as vegetation succession, biomass accumulation, soil accretion and subsidence, and battery formation.

- What were the essential processes that created, shaped, and maintained the predrainage South Florida landscape and how did that landscape support the rich wildlife once present?
- How much spatial extent and landscape heterogeneity must be regained to restore the ecosystem structure and function characteristic of the predrainage system, including support of viable populations of native plants and animals?
- How much sheetflow must be restored to significantly improve habitat value of the system for major indicator organisms and communities in freshwater wetlands and estuaries?
- What were the controlling feedbacks between hydrology, geomorphology, and vegetation in the predrainage system that must be operative for effective restoration?
- Given the influence of basement topography on landscapes, how did hydrologic patterns and rainfall extremes interact with fire and hurricanes to influence fine-scale landscape features?
- What was the predrainage landscape mosaic, and how did it influence hydrologic regime and ecosystem function?
- What were the population responses to that mosaic and what are the minimum needs to support healthy, viable populations?
- What were the critical characteristics of the predrainage landscape mosaic in terms of hydrologic regime and ecosystem function, and how can these characteristics be recaptured?
- How should the hydrologic regime be restored to best reestablish characteristic species and landscapes? What other actions should be taken in concert with hydrologic restoration?
- Given the reduced spatial extent of the central Everglades, how can adequate throughflows be restored to support freshwater inflow needs of ENP and Florida Bay without disrupting structure and function in the central Everglades?
- Can soil rebuilding within the natural Everglades be accomplished by ecosystem restoration? What is the maximum rate of elevation gain that can be expected?
- How do timing, frequency, intensity, spatial coverage, and duration of aperiodic events such as fire, freezes, wind storms, and weather extremes (droughts and floods) affect landscape structure? How have these factors changed from those experienced by the predrainage system?

- How does the landscape respond to sheetflow vs. channelized flow? Understanding is needed of the differences in response (by hydroperiods and hydropatterns, soil moisture, biota, nutrients, and contaminants such as mercury) to coarse channel transport vs. distributed fine channels of sheetflow.
- How are populations of various sizes and types of animals affected by fragmentation and decreased size of habitat? How might establishment of wildlife corridors affect their populations? Given existing spatial distribution, what is the minimum size of available habitat required to support each species?
- How much of each ecosystem type will result from a given restoration alternative (e.g., pocket wetlands, hydric pinelands, tree islands), and how will each type be distributed across the South Florida landscape?
- How and why might restoration of the hydrologic regime restore species or landscapes?
- What processes shape landscape structure, and how are these processes and landscape structure affected by barriers such as roads, levees, and canals?
- What are the landscape-scale ecosystem functions in this system, and how are these functions affected by barriers and by water management?

Recover populations of threatened and endangered species and other selected indicator species.

Models: Individual-based models, other population models.

- What are the habitat requirements for sustainability of populations?
- Will restored hydrologic conditions be favorable to reestablishment of threatened and endangered species?
- What were the wildlife patterns of the predrainage system, and how did they conform to hydrologic and landscape patterns?
- What factors determine nesting site establishment, and how are they related to factors that determine nesting success?
- What are the species' hydrologic requirements for feeding and reproduction? How frequently do conditions for successful nesting occur today, and how frequently would they have occurred in an undrained system? How frequently would favorable conditions have to occur for long-term population stability (e.g., how many years in a 10-year period)?
- What are the species' habitat requirements and the hydrologic requirements of the habitat, and how has water management affected habitat quality?
- What are the relative effects of exotic species, mercury contamination, and hydrology?
- What are the other stresses on populations?

Restore natural and native biological diversity.

Models: Individual-based species models and community models linked to landscape and hydrologic models.

- How will plant and animal communities respond to reestablishment of natural hydrology in various restoration scenarios?
- What is the species richness of bird communities and fish communities?
- How will restoration options affect species richness of selected taxa?

Reestablish natural vegetation and periphyton communities.

Models: Landscape models and succession models.

- What were the original spatial and temporal distributions of vegetation and periphyton communities?
- What factors determined those distributions?
- What is the relative importance of hydrology and nutrients in determining community structure?

Restore natural rates of productivity throughout the ecosystem.

Models: Biomass models that incorporate nutrient cycling; nutrient models that are more than simple stoichiometric models (nonstoichiometric multinutrient models should be undertaken).

- What drives primary and secondary productivity?
- What are the fundamental food webs and major energy and material flows in Everglades wetlands, the Big Cypress, and Florida Bay?

Reestablish sustainable breeding wading bird populations and colonies.

Models: Individual-based models linked to process-based food web models; nesting colony models to evaluate whether various alternative hydrologic scenarios will result in successful breeding at traditional colony sites; models to simulate selection by birds of colony locations under various water management scenarios; models to address not only trophic dependencies but also other habitat requirements of wading birds (e.g., roosting-nesting habitat); models to explore the effect of parasites on fledgling survival and recruitment.

- Why did South Florida lose 90% of its wading birds when only 50% of wetlands were lost? Can changed hydroperiods and hydropatterns explain the loss?
- Why do wading birds no longer occupy the large nesting colonies in the coastal mangrove area of ENP east of the Shark River?

Halt and reverse invasion of the South Florida Ecosystem by exotic plants and animals.

Models: Landscape models that incorporate dispersion and succession components and project invasion rates under different scenarios of water management strategy and other factors such as climate and fire; probability-based invasion models with parameters such as seed pool, distance, and susceptibility properties of the site.

- What factors control the rate of invasion by exotics?

Reduce the input of mercury to the system and its transformation to methylmercury within the system.

Models: Fate and transport models at landscape level; models that simulate physical transport, chemical transformations, and bioaccumulation in food webs as functions of variable controlling factors.

- Why are spatial patterns of mercury concentrations in largemouth bass not correlated with the patterns in soils?

Reestablish corridors.

Models: Animal models embedded in the landscape that show how various landscape patterns affect population processes such as reproduction and migration.

- What are the connectivity needs of a given species or guild?

Increase the hard coral cover on Florida Keys reefs.

Models: Succession models; an ecosystem model that links the reef tract system to seagrass and mangrove systems; linkages to hydrodynamic models that simulate water transport to the reef tract from Florida Bay and links to water quality models of Florida Bay (see section below on water quality/transport models).

- What is the long-term effect on coral cover of water quality changes affecting photosynthesis (e.g., nutrients, light penetration)?
- Are reef tract biota so dependent on seagrasses and mangroves that declines in seagrasses and/or mangroves affect coral reproduction, growth, and survival?
- Can spatial patterns of existing coral cover on the Florida reef tract be explained by differential influences of Florida Bay water in different areas?

Restore natural estuarine and coastal productivity and fisheries.

Models: Seascape models that provide spatially explicit views of estuaries and how salinity patterns, as established by freshwater inflow, overlap with habitat features important to estuarine-dependent species (these could be used to predict overall abundance of selected species as a function of acreage of overlap of favorable salinities with favorable habitat); estuarine models that link seagrass, mangrove, and water-column communities and indicate nutrient cycling and conditions related to water quality (see below); landscape-scale biomass models that include nutrient cycling; fishery population models that relate growth and survival to habitat, salinity, and temperature.

- How much of an increase in overall estuarine production can be expected from a given increase in freshwater flow to Florida Bay?
- How much of an increase in seagrass coverage can be expected from a given increase in freshwater flow or a given decrease in concentration of nutrients?
- Could nutrients released from death and decay of seagrasses alone be responsible for observed bluegreen algal blooms?

Link agricultural and urban growth management with ecosystem management.

Models: Landscape-scale ecologic models linked to agricultural and urban growth models through hydrologic models.

- What are the critical feedbacks of the natural system to urban and agricultural systems and vice versa?
- How will the natural system and its support functions for humans be affected by different population levels and land-use configurations?

Restore a system that is self-maintaining with minimum human intervention.

Models: A model that integrates over all spatial scales.

- What is the landscape configuration and water regime that will provide a high degree of restoration with the lowest maintenance requirements?

Objectives

The objectives of ecologic modeling are to:

- Formulate a protocol for applying models in environmental assessment.

- Build a suite of models to: 1) address science questions related to the restoration objectives and the adaptive management process and 2) simulate restoration assessment indicators.
  - These models must be both assessment tools and integral components of science efforts to support restoration management.
  - They will be systems of linkable models that can simulate processes operating at several scales as functions of hydrologic conditions and other driving forces, as affected by major stresses such as droughts, floods, hurricanes, fire, and freezes.
  - They will embody current understanding of the system and be designed to accept the simulated output of hydrologic or hydrodynamic models directly or through other models.
  - They will assist in evaluating water management alternatives for their potential to improve ecosystem health.
  - Model results will be testable to allow the models to be improved as part of the adaptive assessment process.

- Integrate modeling with development of a monitoring plan and plans for special science studies.

Current Modeling Activities

Many ecologic modeling activities to support the South Florida Ecosystem Restoration effort have already been started by various agencies. Several models are under development, and some are near the application stage. These include DeAngelis et al. undated(a),(b); Fleming et al. 1994, 1995, in press(a),(b), submitted; Fong and Harwell 1994; Wolff 1994; and Wu et al. 1993a,b.

National Biological Service

ATLSS. The NBS in Miami, in cooperation with ENP, Oak Ridge National Laboratory, Chesapeake Biological Laboratory, and Florida International University, is developing a modeling system called "Across-Trophic-Level System Simulation" (ATLSS) for application to South Florida restoration issues. ATLSS consists of: 1) an integrated system of spatially explicit simulation models of major trophic groups that will be coupled through a spatially explicit landscape structure that accepts information on elevation and vegetation as well as outputs of hydrologic and landscape models; 2) trophic flow-network ecosystem analysis to identify the primary ecological components in each system, exchanges of energy and material among them, and recycling pathways for carbon, phosphorus, and nitrogen; and 3) coupling of ATLSS with flow-network analysis models to evaluate outputs of simulation models and provide a quantitative view of changes in system trophic structure and function and resultant changes in stocks and major nutrient cycles under various scenarios of water management strategy or other anthropogenic controls.

Modeling of trophic groups will take three approaches: 1) lower trophic level organisms will be represented with process-oriented models, 2) intermediate trophic level organisms will be represented with age- and size-structured aggregated population models, and 3) higher order vertebrates such as wading birds will be represented with individual-based models. These trophic-level models will be coupled as described in 1) in the paragraph above.

This modeling effort is fully integrated with science projects being conducted in the Everglades/Big Cypress region and will allow interpretation of results at the whole-system level. Progress has been made in individual-based models for wood storks, Florida panthers, alligators, and Everglades white-tailed deer; aggregated models for the freshwater fish community; and a process-oriented model for the periphyton community. In the latest initiative, a regional-scale model is being developed that simulates feeding and nesting activity and fledgling production of four wading bird species with distinct energetic and behavioral characteristics.

ATLSS will provide a rigorous integrative approach for testing hypotheses related to chronic stresses on the system and their interactions with major pulse disturbances such as hurricanes. This is critical to formulation of a system-wide restoration plan within the context of regional water management.

GAP. Biodiversity modeling at the landscape scale is the goal of the South Florida Biological Diversity Project planned at the NBS Florida Cooperative Fish and Wildlife Research Unit in Gainesville as part of the State's Gap Analysis Program (GAP). It is the first step in a nationwide program to assess how much existing biological diversity falls within lands that are managed in some way for natural resource protection. GAP is a proactive approach to protecting biological diversity using surrogates, such as land cover and species richness, to assess conservation value of large geographic areas. By mapping land cover, modeling potential vertebrate habitat based on land cover and other spatial data, and overlaying modeled habitats, species richness can be spatially determined and compared to areas set aside for conservation. Areas of high species richness that fall outside of conservation area boundaries are referred to as "gaps" in protection. The method is quick and cost-effective because it is based on remote sensing and computerized habitat classification and mapping. The Biological Diversity Project will provide 1) a base for existing land cover and potential habitat richness and 2) a quick, cost-effective model for estimating change in potential habitat richness as a result of restoration alternatives.

In preparation for this project, Landsat thematic mapper imagery has been obtained for the entire State. Image classification and existing spatial information on topics such as soils will be used to map habitat. Land-use classification will be based on the Florida Natural Areas Inventory and the Florida Heritage Program of The Nature Conservancy. Distribution and habitat association data are being compiled from museum records, literature, and consultation with experts for all species of terrestrial mammals, breeding birds, and butterflies in the State.

Distribution data are used to restrict the range. Within that range, knowledge of wildlife species habitat preferences is used to build a model of potential habitat. The models may use land-cover type, minimum viable areas, proximity to other necessary land covers (e.g., for some birds, nesting requires a specific land-cover type within a certain distance of another land-cover type where the bird forages), and other spatial metrics.

Grid coverage with multiple attributes, one for each modeled species, will be used to store results of the potential habitat models. Several coverages with differently sized grids will be created, and each species will be associated with the coverages that best reflect the scale of its response to its environment (e.g., a pig frog responds to a smaller immediate environment than a Florida panther). The final layer of information is coverage of the boundaries of lands set aside for conservation. This includes Federal and State parks; NWRs and other wildlife areas; SFWMD lands; county and municipal parklands maintained as natural areas; and lands owned by the National Audubon Society, The Nature Conservancy, and other conservation groups. When this coverage is compared to the species richness products, areas of high biological diversity not within protected areas can readily be identified.

National Oceanic and Atmospheric Administration

Shrimp population models. Statistical and simulation population models are being conducted by NOAA/NMFS that relate pink shrimp to juvenile estuarine habitat and environmental variables such as freshwater inflow. Resource surveys, physiological trials, and genetic analyses of pink shrimp will support the modeling. The study will characterize the within-year cohorts in the fishery and link them to specific nursery grounds in Florida Bay and nearby estuaries. The pink shrimp is viewed as a potential indicator of ecological health of Florida Bay. Pink shrimp catch rates suggest a long-term stock decline, with an increasing rate of decline in the past decade. The study is designed to gain understanding on how natural variability and anthropogenic manipulation of freshwater inflow affect pink shrimp recruitment.

Seagrass linkage models. NOAA/NMFS has initiated field activities to explore the linkage between seagrass and mangrove habitats. The seagrass dieoff in Florida Bay has caused changes in fisheries habitats and species composition. Juveniles of many species are being forced to use alternative habitats. A NOAA/NMFS and FDEP cooperative effort will develop an ecologic model incorporating linkages between habitats to gain an understanding of pre- and post-dieoff community composition. This information will be used to predict changes in utilization with restoration.

A primary producer model that simulates feedback between water quality and ecosystem structure, as influenced by nutrient loading, is proposed. Seagrass beds not only are influenced by nutrient availability but also influence nutrient concentrations. The model would explore the interactions of seagrass beds with nutrient cycling.

Salinity models. NOAA/NMFS has begun a spatial study of Florida Bay that examines distributions and densities of living resources in relation to the overlap of dynamic and relatively stable habitat features. Initially the project is evaluating the influence of diurnal and seasonal changes in water depth. In subsequent years, it will examine salinity patterns, superimposed over bottom and shoreline habitat. The study will examine how freshwater inflow affects the area of overlap of favorable salinities with favorable bottom features for juveniles of various species. This will enable prediction of changes in bay "production capacity" with changes in freshwater inflow. This modeling activity will integrate and interpret, in an ecological context, bottom habitat maps from NOAA's Coastal Change Analysis Program and salinity maps using an airborne sensor in a proposed cooperative study involving NOAA/NMFS, NOAA/AOML, and NOAA's National Environmental Satellite, Data, and Information Service.

NESDIS and NMFS propose to perform synoptic mapping of Florida Bay with a light-weight, GPS-logged, airborne salinity sensor. Determining the relationship between freshwater discharge and salinity patterns is critical to the overall Florida Bay restoration effort. Salinity patterns in the bay are complex because of the basin-bank topography, wind effects on water movement, and number of locations of freshwater input. The most practical and accurate way to map salinities is with the airborne sensor, which is a specialized microwave radiometer designed for this use. Groundtruthing will be used initially to ensure accuracy of the salinity instrument for Florida Bay. This effort will produce paper and digital salinity maps for use in the NMFS productive capacity study. The data can be used to calibrate and validate hydrodynamic models of Florida Bay that are under development.

South Florida Water Management District

The Everglades Landscape Model under development by SFWMD is a promising concept with potential use in ecological assessment. ELM is a grid-based biomass model that incorporates its own hydrologic model. Operating at appropriate time scales, it could simulate ecosystem evolution and geomorphologic development, with vegetation succession and hydrologic regime interacting. ELM development should be coordinated with other modeling and research activities such as ATLSS.

Environmental Protection Agency

The Athens Environmental Research Laboratory has begun an investigation to understand the environmental factors that influence rates of microbial mercury methylation and demethylation, identify sources and transport patterns of mercury consistent with current conditions and historic changes in the Everglades, and evaluate mitigation and control strategies. Mercury modeling is discussed more extensively in the chapter on mercury.

Approach and Scope

Sets of models that can integrate the ecological system across spatial and temporal scales will be the most useful for the restoration effort because they will give scientists the ability to understand and predict interrelated processes operating from microhabitat to landscape levels. Species-, community-, and landscape-level models are all needed to address the science issues and questions listed above. Ecologic modeling activities should include, at a minimum, individual-based, population, trophic-dynamic, process-oriented, community, and landscape models. For instance, understanding the entry of mercury into the ecosystem, its transformations, and how it accumulates in animals at all stages of the food chain is an important question that requires models capable of integrating across several scales.

Species-level models can help identify the critical interactions of various plant and animal species and the influence of landscape and hydrologic patterns. Certain species, by their recruitment or behavior, act as sensitive indicators of ecosystem function. For instance, wood storks and snail kites, because of their wide foraging areas and specific foraging requirements, reflect ecosystem functioning at the landscape level in their recruitment. Other species are of interest because of their threatened status. Models are needed to test effects of water management options on such species.

Community-level models could simulate ecosystem processes operating in periphyton communities in the freshwater Everglades, nuisance algal blooms in Florida Bay, freshwater macrophyte communities experiencing a change in species dominance, and fish communities supporting colonial nesting wading birds. The need to control the spread of invasive non-native species into native plant communities is another concern that could be addressed by community-level modeling.

Florida laws suggest other community-level modeling needs. The water quality standard states discharges into protected waters should not cause an "imbalance" in natural plant and animal communities. But what constitutes imbalance? Models are needed to address the concept of ecological balance in a descriptive and quantifiable sense. As another example, the SFWMD is required by State law to determine minimum flows for freshwater wetlands and estuaries. Estuarine models capable of relating freshwater flow to ecosystem productivity and natural resource abundance are needed to help define minimum flows.

The landscape not only is influenced by the hydrologic regime but also influences this regime by affecting flow rates and defining flow paths. Land contours are influenced by vegetation growth and the hydrologic regime through their effects on soil accretion and subsidence and battery formation. Patterns of land and water influence reproductive activities of wading birds, deer, and other animals. The understanding of issues related to these topics requires landscape models in interaction with other models. Landscape modeling is dependent upon hydrologic modeling and needs to be fully integrated with hydrologic modeling studies to address questions concerning ecosystem and wildlife responses to restoration actions. Landscape models must also be applied in concert with trend and gradient analyses and retrospective paleoecological investigations. Models and paleoecological results can be mutually supportive in terms of describing prior conditions.

Restoration requires a historical representation. Quantitative descriptions of the hydrology and ecology of the predrainage system are lacking, although paleoecology may someday provide information on this topic. Meanwhile, the best guide for understanding the ecological ramifications of changes in spatial extent and hydrologic conditions that have occurred since predrainage days will be spatially explicit "natural system" hydrologic models, with control structures removed and topography restored to approximate the predrainage system, supporting a system of ecologic simulation models that operate at several scales and are spatially explicit at the landscape level.

A GIS-based, spatially explicit landscape model should be developed that could be used not only to examine present landscape structure in relation to hydrologic forces but also to recreate the predrainage landscape. The approach should be to start with the basement structure and use the natural hydrologic model, in conjunction with the landscape model, to accumulate soil and create a landscape as a function of the basement structure, hydrologic conditions, and forcing events such as fire, rainfall extremes, sea-level rise, and climate change. The consequences of various scenarios of control structure configurations and operation strategies could be shown in terms of the mix of ecosystems and landscape mosaics that result.

Surficial topography and landscape result from forces acting on the basement substrate. They arise from accumulation of soil and peat. To predict the outcome of restoration actions, soil accretion and subsidence should be modeled as functions of water depths, hydroperiods, fire regimes, vegetation, and other influencing factors. Estimates of rates of soil accumulation and landscape building are needed to support this model usage. A landscape model might be verified by imposing the C&SF Project on the predrainage landscape and simulating the landscape change over time. The resulting landscape can then be compared to the present landscape.

One of the most important uses of this landscape model should be to determine how changes in landscape influence the hydrologic regime, including flow rates, hydroperiods, and hydropatterns. While it is known that vegetation patterns influence water flow, the effect of landscape change on water patterns in this system has not been examined. A vegetative landscape model is needed that will be responsive to the dynamics of hydropattern and water quality over time and space. To address the science questions, this model must be responsive to conditions that vary on seasonal, annual, and decadal time frames and involve water management changes, climatic change, and events ranging from fire to rainfall extremes, freezes, and hurricanes. Essentially, what is needed is a model that will simulate landscape development, including vegetation succession, soil formation and dissolution, and change in elevations. Such a model will be most effective if used interactively with spatially explicit hydrologic models, where it would provide a dynamic landscape that influences water flow and surface water patterns.

Ecologic modeling activities must include three requisite tasks: 1) actual model development, 2) identification of ecological assessment indicators, and 3) design of an assessment protocol and framework.

▸ Model Development

Ecologic model development should begin at the start of the restoration effort and be fully integrated with all science and monitoring projects. Only the development and application of ecologic models, even with cursory data, can reveal the types of information needed from hydrologic and hydrodynamic models and demonstrate why they are necessary. Prior to model development, existing methods for calculating growth projections, land-use changes, and related water demand and changes in water tables and water management must be reviewed.

ATLSS contains many powerful and promising modeling concepts, as described above and presented at a June 1994 workshop sponsored by the SSG. Properly directed, this modeling system can be particularly useful for evaluating alternative management options and measuring restoration progress. The NBS-GAP initiative, also described above, is another approach that appears valuable to the restoration effort. It is a cost-effective means of region-wide analysis and addresses many needs of the South Florida subregions (see following chapters). GAP provides a multispecies approach to optimizing native biodiversity, recovering protected species, and controlling exotic invasions from a habitat perspective.

The complementary ELM and ATLSS projects can be considered a landscape studies program already underway. The program needs further support and some reorientation to meet the needs of the restoration effort. ELM, because it is spatially explicit, could be useful for simulating soil building processes; land recontouring;

formation of tree islands, sloughs, sawgrass stands, batteries, etc.; and effect of vegetation patterns on water flow, hydroperiods, and hydropatterns. The ATLSS landscape model will be most useful for understanding animal responses to the current landscape and those resulting from various restoration alternatives.

ELM, because it is biomass based and incorporates its own hydrologic system, could be the basis of the landscape model needed to generate landscape development in interaction with hydrologic regime, if the model is designed to keep track of soil building and depletion and to operate over near-geologic time scales. To be most useful to the restoration effort, this model also must be expanded beyond the WCAs and ENP. ELM should be networked or coupled with species assessment models ranging from habitat-related statistical models to individual-based species models. ELM, at its present resolution, will not capture the structural and process detail required to adequately evaluate all the important responses of the system to restoration. Therefore, subgrid-scale models within ELM should be developed at finer resolutions.

Further development of both ATLSS and ELM should be integrated with development of a restoration assessment protocol (see below). Some guidance, as well as communication between modelers, should ensure that the models are serving complementary needs.

Seascape models that provide spatially explicit views of estuaries also are needed in the restoration process to show how salinity patterns, as established by freshwater inflow, overlap with habitat features important to estuarine-dependent species. Initially, attention should focus on Florida Bay. A model should be developed that will 1) include bottom topography and the Overseas Highway and 2) integrate spatial information on salinity, circulation patterns, and nutrients. Hydrodynamic models should be designed to provide salinity to this model.

Conceptual models also have a role in the restoration effort. Models in the form of diagrams and descriptions are a good way to integrate and communicate information and ideas. They are good organizing tools at study inception and can provide the initial design basis for simulation models.

▸ Identification of Ecological Assessment Indicators

Those species and communities that play especially important roles in ecosystem function would be appropriate subjects for models that simulate ecological assessment measures. Subjects chosen should be sensitive to the types of changes being made. Species should be selected that will represent groups of species with different habitat requirements. For instance, the wood stork and snail kite would be complementary, both having different responses to hydrologic regime. The American alligator might be another complementary addition to this selected group. Species that are indicators of region-wide ecosystem function would be particularly useful. The wood stork and other wading birds are examples of this type because their feeding ranges are large and, by their choices of colony sites and their reproductive success, they integrate information on secondary productivity and hydropatterns across broad areas. Recruitment of pink shrimp, because they are a major prey of many fish species, represents overall productivity of the estuarine ecosystem.

Initially, ecological assessment measures should be based on those species and communities to which considerable scientific attention has been given in the past so that both the time series of data and an intellectual basis for model design are available. In addition, other key species or communities should be identified for new research that will make it possible to measure restoration success by their responses. For instance, the apple snail is the critical prey of several species, yet little is known about its population biology and ecology. Filling this deficiency is an important need.

▸ Design of Assessment Protocol and Institutional Framework

The design of an assessment protocol should be done in concert with model development to ensure that a workable and effective assessment procedure evolves. The protocol should take advantage of models under development that have already demonstrated some promise. Further model development should take place interactively with protocol development.

An institutional framework to support ecologic modeling is essential to the restoration effort because models are critical to the application of adaptive management methodology. Models must be developed, refined, and maintained; therefore, models need continuous funding and a home.

The SSG should formulate a plan that contains a suggested assessment protocol and institutional framework. The plan should identify core models and a workable set of measurable ecological indicators. To be useful, models must simulate these indicators or data from which they can be derived. Protocol design should take into consideration information that can be generated by models presently under development.

Information Needs and Recommendations

Many specific information needs related to ecologic modeling were discussed throughout this section. Overall recommendations are:

- Integrate model development with development of a restoration assessment protocol.

- Design integrated modeling systems in which ecosystem models accept output of hydrologic and landscape models and interpret these outputs in an ecosystem context.

- Encourage and nurture the promising modeling concepts of ATLSS by providing: 1) continuous funding at an increased level; 2) guidance to ensure the models will simulate selected ecological assessment measures or indicators; and 3) access of modelers to - and communication with - a wide group of authorities on the species and communities being modeled to ensure incorporation of the best available information and widespread acceptance of the models by the scientific community.

- Support the Florida GAP initiative to help it meet objectives of the South Florida Restoration effort. Fill the "gaps" in GAP funding.

- Support the independent landscape modeling initiatives started by the SFWMD and NBS/ENP/ORNL and give them more direction to enhance usefulness of the models for ecosystem restoration.

- Develop models that provide spatially explicit views of estuaries to determine how salinity patterns, as established by freshwater inflow, overlap with habitat features important to estuarine-dependent species.

- Encourage several ecologic modeling approaches, and consider the full range of potentially useful models in the context of the suite of capabilities that are needed. Models or modeling systems that can integrate the ecological system across scales appear the most useful, but the door should not be closed to other modeling approaches because modeling science, like the biological world, is evolving, and diversity provides the basis for successful adaptation.

- Support trend and gradient analyses and retrospective paleoecological studies as part of a landscape studies program that includes landscape models.

- Use conceptual models to integrate information, communicate ideas, and share understanding on a topic.

- Establish an institutional framework, including a home and continuous funding at an increased level, to support development and continued upgrading and application of ecologic models.

MODELING WATER QUALITY/TRANSPORT PROCESSES

Background

Water quality is a major concern in the South Florida Ecosystem. With respect to the Everglades and Lake Okeechobee, the principal focus has been on eutrophication, primarily due to excess phosphorus entering natural

areas in agricultural runoff. Urban runoff also is a nutrient-laden source of pollution for the Everglades and is likewise degrading the Florida Keys coral reef tract and parts of Florida Bay.

Contaminants are another threat to environmental health in South Florida. Mercury has been the principal focus of recent activities. Some of the organic compounds applied intensively in South Florida to control pests and weeds in both agricultural and urban settings are also damaging to natural systems. Pollution is a significant and expanding problem in South Florida.

Several management actions to reduce nutrient loads to Lake Okeechobee and the Everglades are in place or under development through State and Federal cooperation. The most recent and significant of these are implementation of Best Management Practices and creation of Stormwater Treatment Areas, as mandated under the State's Everglades Forever Act. Efforts concerning contaminants in the South Florida Ecosystem have primarily focused on mercury. Research needs relevant to modeling the transport and fate of mercury are discussed in the chapter on mercury.

Water quality/transport models that can be linked to hydrologic models are needed to study the transport and fate of both nutrients and contaminants and to determine how transport and fate (and subsequently the health of the ecosystem) might be affected by present and proposed water management actions, as well as direct efforts to control application and movement of contaminants.

Issues

The major issues that will be addressed by water quality/transport modeling are:

- Eutrophication of Lake Okeechobee, the Everglades, Florida Bay, and the St. Lucie River-Indian River estuary.
- Contamination of freshwater wetlands and estuaries with mercury and biologically active organic compounds such as endosulfan.

Objectives

The objectives of a water quality modeling program should be to:

- Integrate water quality modeling with other models.
- Expand water quality modeling into the mangrove zone, Florida Bay, Florida Keys National Marine Sanctuary, and Southwest Florida.
- Develop the capability to predict and describe changes in water quality that may occur with water management changes.
- Support the study of transport and fate of anthropogenic nutrients and contaminants in the ecosystem and the design of structural and operational changes and other management actions to reduce their release into the environment.

Current Modeling Activities

South Florida Water Management District

The SFWMD currently is funding development of a water quality/transport model that can be linked to the SFWMM and SFRSM. This model examines only first-order phosphorus interactions and does not consider effects of biological interactions. The ELM integrates water quality modeling with hydrologic, landscape, and biomass modeling through a component that includes nutrient uptake and cycling. The SFWMD also conducts modeling activities in association with the Everglades Nutrient Removal site, where experiments related to the future STAs are being conducted. The COE and NPS will be working with the SFWMD in these water quality modeling efforts.

Tetra Tech

With funding from the Sugarcane Growers Cooperative of Florida, Tetra Tech of Pasadena, California, developed the Everglades Phosphorus and Hydrology Model to look at water movement from the EAA through the WCAs and into ENP and phosphorus removal from water that flows from the EAA. Only first-order phosphorus removal is examined.

University of Miami

The UM Center for Marine and Environmental Analyses, with funding from the COE, is adapting a seagrass unit model to a full-scale seascape model for Biscayne Bay. The model will examine exchanges of nutrients among water column, sediment, seagrass, epiphyte, and phytoplankton compartments.

University of Florida

The University, with funding from the SFWMD and The Nature Conservancy, has developed a simplistic coupled seascape-hydrodynamic model of Florida Bay to explore the interactions of seagrasses, phytoplankton, substrate, and nutrients. This is a screening model referred to as an Adaptive Environmental Management Model. It will demonstrate how coupled hydrodynamic-ecosystem models can be used to examine hypotheses about causes of water quality problems and to test alternative proposed solutions.

Approach and Scope

The first step in a water quality modeling program for South Florida should be to develop a system-wide nutrient budget that accounts for nutrient fluxes from one part of the ecosystem to another, from the Kissimmee River to Florida Bay and the FKNMS. Water quality models should be developed that incorporate biological as well as physical processes. Water quality modeling should be based on a landscape-level ecosystem model that integrates hydrologic, water quality, and biomass modeling. The ELM is a beginning in this effort, but it needs to be expanded geographically to include Lake Okeechobee, Florida Bay, the EAA, and the sparsely developed wetlands east of the Eastern Protective Levee, where a buffer system (East Coast Buffer/Water Preserve Areas) is proposed. Eventually, this model should be expanded to cover the Big Cypress and the rest of Southwest Florida.

A landscape-scale ecosystem model that integrates energy and nutrient flows among substrate, water column, and biologic compartments (seagrass, epiphytes, and phytoplankton) and is linked to a hydrodynamic model is the suggested approach to a water quality model for Florida Bay. The UF model (above) provides a simplistic representation of the coupling of physical and biological processes that is needed.

Information Needs and Recommendations

- Conduct a scoping effort concerning geographic expansion of the ELM.

- Initiate a planning effort to develop an integrated biomass and water quality model for Florida Bay, which should be linked to the hydrodynamic model underway and expanded to cover transport of water masses (including nutrients, phytoplankton, salinity, and temperature) between Florida Bay and the Florida Keys reef tract. This effort should take advantage of input from the UF and UM modeling efforts.

- Initiate a planning effort regarding water quality modeling to support the design of water treatment in conjunction with the East Coast Buffer concept and the Everglades Experimental Water Deliveries program.

BIBLIOGRAPHY

Blumberg, A.F., and G.L. Mellor. 1987. A description of a three-dimensional coastal ocean circulation model. Pages 1-16 *in* N.S. Heaps, editor. Three-Dimensional Coastal Ocean Models. Coastal and Estuarine Sciences 4. American Geophysical Union, Washington, D.C.

Burpee, R.W. 1979. Peninsula-scale convergence in the south Florida sea breeze. Monthly Weather Review 107:852-860.

Burpee, R.W., and L.N. Lahiff. 1984. Area average rainfall variations on sea breeze days in South Florida. Monthly Weather Review 112:520-534.

DeAngelis, D.L., L. Gross, Y. Wu, D.M. Fleming, O.L. Bass. Undated(a). C-111 Assessment for Florida panther. Institute for Environmental Modeling, UT, Knoxville, Tennessee.

DeAngelis, D.L., L. Gross, D.M. Fleming, and O.L. Bass. Undated(b). Scope of work for Everglades National Park Environmental studies for Central and Southern Florida Flood Control Project Canal-111.

DeMaria, M., S. Aberson, K.V. Ooyama, and S.J. Lord. 1992. A nested spectral model for hurricane forecasting. Monthly Weather Review 120:1628-1643.

DeMaria, M., C. Mattocks, and M. Powell. 1994. Report of the First South Florida Atmospheric Modeling Workshop. November 29, 1994. Hurricane Research Division, NOAA/AOML, Miami, Florida.

Droegemeier, K.K, M. Xue, P.V. Reid, J. Bradley, and R. Lindsay. 1991. Development of the CAPS Advanced Regional Prediction System (ARPS): an adaptive, massively parallel, multi-scale prediction model. Pages 289-292 *in* preprints of the 9th Conference on Numerical Weather Prediction, Denver, Colorado. American Meteorological Society, Boston, Massachusetts.

Fennema, R.J. 1992. Natural System Model. An evaluation of version 3.4. Report to the NPS, ENP, Homestead, Florida.

Fennema, R.J., C.J. Neidrauer, R.A. Johnson, W.A. Perkins, and T.K. MacVicar. 1994. A computer model to simulate natural South Florida hydrology. Pages 249-290 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Fleming, D.M., D.L. DeAngelis, L.J. Gross, R.E. Ulanowicz, W.F. Wolff, W.F. Loftus, and M.A. Huston. Submitted. ATLSS: Across-Trophic-Level System Simulation for the freshwater wetlands of the Everglades and Big Cypress Swamp. NBS Technical Report Series.

Fleming, D.M., D.L. DeAngelis, and W.F. Wolff. 1995. The importance of landscape in ecosystem integrity: the example of Everglades restoration efforts. Pages 202-217 *in* L. Westra and J. Lemons, editors. Perspectives on Ecological Integrity. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Fleming. D.M., J. Schortemeyer, and W. Hoffman. In press(a). Colonial wading bird distribution and abundance in the pre- and post-drainage Everglades landscapes. Oecologia.

Fleming. D.M., J. Schortemeyer, and W. Hoffman. In press(b). Colonial wading bird nesting in the pre- and post-drainage Everglades landscapes. Oecologia.

Fleming, D.M., W.F. Wolff, and D.L. DeAngelis. 1994. The importance of landscape heterogeneity to wood storks in the Everglades. Environmental Management 18:743-757.

Fong, P. and M.A. Harwell. 1984. Modeling seagrass communities in tropical and subtropical bays and estuaries: a mathematical model synthesis of current hypotheses. Bulletin of Marine Science 54(3):757-781.

Fourqurean, J.W., B.J. Cosby, W.K. Nuttle, M.B. Robblee, and J.C. Zieman. 1995. Development of FATHOM: a mass-balance model for the simulation of salinity and circulation in Florida Bay. Draft report to NPS, ENP, Homestead, Florida. Southeast Environmental Research Program, Department of Biological Sciences, FIU, Miami, Florida.

Galperin, B., M.A. Haines, and M.E. Luther. 1995. The design of a modeling strategy for Florida Bay. Report to NPS, ENP, Homestead, Florida. University of South Florida, Tampa, Florida.

Mellor, G.L. 1992. User's guide for a three-dimensional, primitive equation, numerical ocean model. Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, New Jersey.

Powell, M.D., and S.H. Houston. 1993. Surface wind field analyses in Hurricane Andrew. *In* Proceedings: 7th U.S. National Conference on Wind Engineering, UCLA, June 27-30, 1993.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Sheng, Y.P., J. Davis, and Y. Liu. 1995a. Numerical simulation of tidal circulation in Florida Bay. Report to NPS, ENP, Homestead, Florida. Coastal & Oceanographic Engineering Department, UF, Gainesville, Florida.

Sheng, Y.P., Y. Liu, and J. Davis. 1995b. Continued numerical simulation of tidal circulation in Florida Bay. Report to NPS, ENP, Homestead, Florida. Coastal & Oceanographic Engineering Department, UF, Gainesville, Florida.

Wang, J.D. and C. Monjo. 1995. A study to define model and data needs for Florida Bay. Report to the NPS, ENP, Homestead, Florida. Division of Applied Marine Physics, RSMAS, Miami, Florida.

Wolff, W.F. 1994. Individual-oriented model of a wading bird nesting colony. Ecological Modelling 72:75-114.

Woodley, W.L., J. Jordan, A. Barnston, J. Simpson, R. Biondini, and J. Flueck. 1982. Rainfall results of the Florida Area Cumulus Experiment, 1970-1976. Journal of Applied Meteorology 21:139-164.

Wu, Y., L. Gross, D. DeAngelis, D.M. Fleming, and O.L. Bass. 1993a. A spatially explicit individual-based model for Florida panther in the Everglades landscape. Unpublished manuscript on work in progress. Institute for Environmental Modeling, UT, Knoxville, Tennessee.

Wu, Y., L. Gross, D. DeAngelis, D.M. Fleming, and J. Schortemeyer. 1993b. SIMDEL: A spatially explicit, individual-based model for white-tailed deer in the Everglades. Unpublished manuscript on work in progress. Institute for Environmental Modeling, UT, Knoxville, Tennessee.

SUBREGION 1:

KISSIMMEE RIVER BASIN

INTRODUCTION

This chapter presents a summary of information needs for ecological monitoring and evaluation of the restoration of the Kissimmee River and several of its headwater lakes. This restoration is being conducted by the COE (Jacksonville District) and the SFWMD. The information and science strategies described are a compilation of studies in advanced stages of planning or early stages of implementation and do not represent a new agenda. The scientific studies described were developed under the leadership of the SFWMD with input from the COE, FGFWFC, and FWS. In addition to ecological monitoring, hydraulic, sedimentation and structural stability monitoring will also occur; however, these are not the focus of this chapter and are discussed only briefly. Figure 9 outlines the objectives and scientific information needs under the overall restoration goal. These are based on ecological and hydrological objectives for Subregion 1 developed by the Science Subgroup (SSG 1993) and on objectives and tasks outlined in the draft Kissimmee River Research Plan (SFWMD 1994; see Figure 2 of appended plan).

Notable references on the Kissimmee River are the proceedings of the 1988 Kissimmee River Restoration Symposium (Loftin et al. 1990b), which contains 24 papers, and Volume 3(3) of *Restoration Ecology* (Dahm 1995), a special issue dedicated to Kissimmee River restoration that contains 8 papers. These publications are cited as single documents; each paper is not listed individually.

BACKGROUND

The 7804-km^2 (3013-mi^2) Kissimmee River basin begins south of Orlando and extends southward about 145 km (90 mi) to Lake Okeechobee (Figure 1). The area is frequently divided into upper and lower basins. The upper basin contains a series of connected lakes, of which Lakes Tohopekaliga, Hatchineha, Cypress, and Kissimmee are the largest. The lower basin contains Canal-38, remnants of the Kissimmee River, and six water control structures.

The basin has been modified for navigation and flood control purposes since the 1890s; however, the most significant modifications occurred between 1962 and 1971 as a result of the Central and Southern Florida Flood Control Project, which authorized the Kissimmee River portion in 1954. That project established a regulation schedule for the upper basin lakes and created a 90-km (56-mi) canal in place of the 166-km (103-mi) Kissimmee River. Six structures in C-38 maintain water elevation, control water releases, and provide lockage.

MAJOR ISSUES

The impacts of flood control, navigation, agriculture, and development in the Kissimmee basin are well documented, and the reader is referred to Loftin et al. (1990a, 1990b), Carroll and Banner (1991), and COE (1991) for additional detail. Loftin et al. (1990a) captured the essence of the impacts of channelization: "... in addition to direct physical destruction of the river and floodplain habitat which resulted from canal excavation and deposition of soil, channelization has ... impacted the ... ecosystem primarily through altered hydrologic regimes. Ecological consequences ... include diminished floodplain habitat diversity, reduction of wading bird usage of the floodplain, and loss of habitat for forage fish, as well as larger riverine fish species. The nature and rate of energy exchange between the river and floodplain also has been disturbed. Elimination or modification of the river/floodplain interactions has affected the functional integrity of both the river and floodplain. ...Lack of flow has degraded water quality, and led to excessive sedimentation ... diminished habitat quality and diversity, and degraded river biological communities."

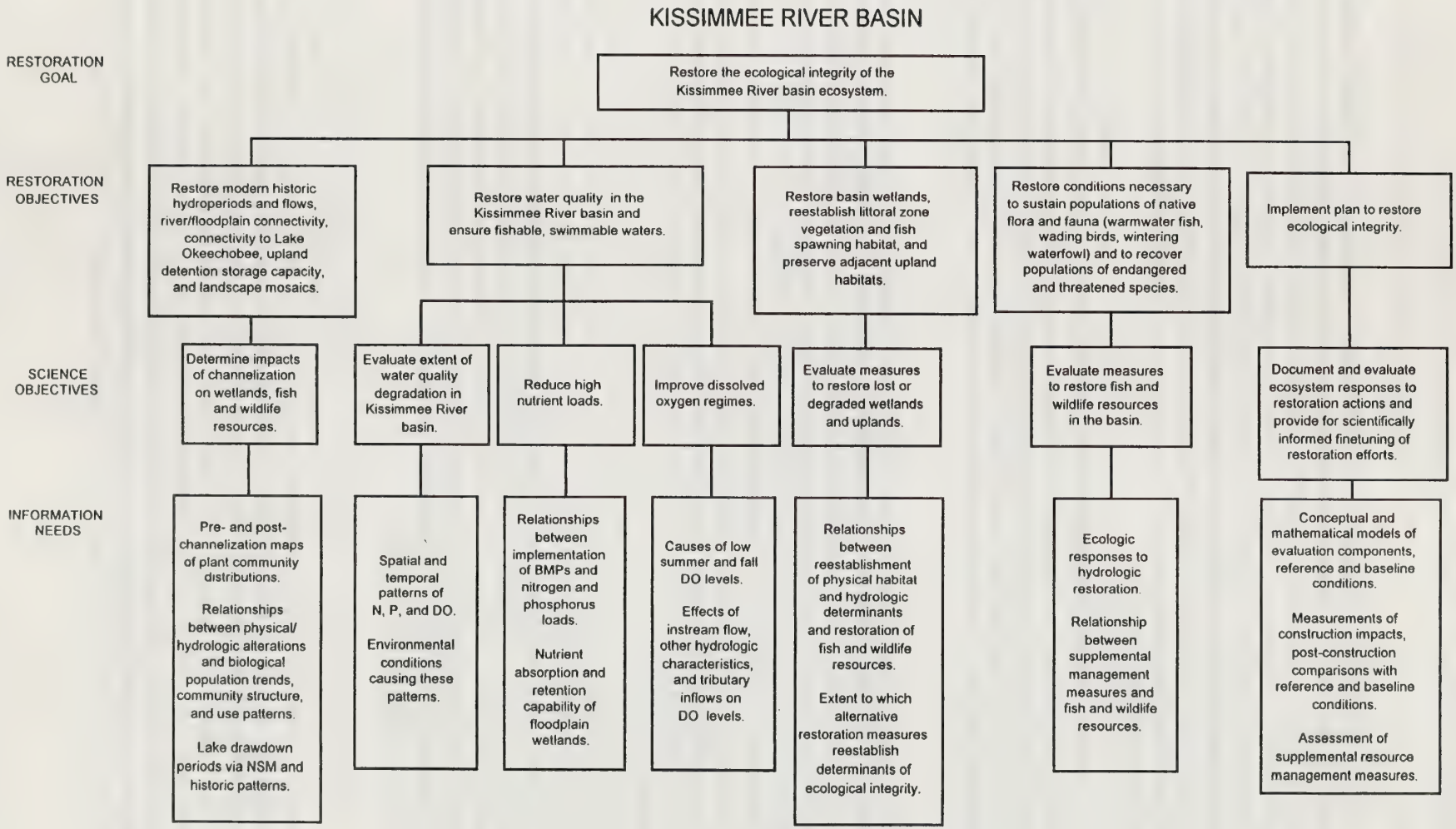

KISSIMMEE RIVER BASIN
RESTORATION GOAL
Restore the ecological integrity of the Kissimmee River basin ecosystem.
RESTORATION OBJECTIVES
Restore modern historic hydroperiods and flows, river/floodplain connectivity, connectivity to Lake Okeechobee, upland detention storage capacity, and landscape mosaics.
Restore water quality in the Kissimmee River basin and ensure fishable, swimmable waters.
Restore basin wetlands, reestablish littoral zone vegetation and fish spawning habitat, and preserve adjacent upland habitats.
Restore conditions necessary to sustain populations of native flora and fauna (warmwater fish, wading birds, wintering waterfowl) and to recover populations of endangered and threatened species.
Implement plan to restore ecological integrity.
SCIENCE OBJECTIVES
Determine impacts of channelization on wetlands, fish and wildlife resources.
Evaluate extent of water quality degradation in Kissimmee River basin.
Reduce high nutrient loads.
Improve dissolved oxygen regimes.
Evaluate measures to restore lost or degraded wetlands and uplands.
Evaluate measures to restore fish and wildlife resources in the basin.
Document and evaluate ecosystem responses to restoration actions and provide for scientifically informed finetuning of restoration efforts.
INFORMATION NEEDS
Pre- and post-channelization maps of plant community distributions.
Relationships between physical/ hydrologic alterations and biological population trends, community structure, and use patterns.
Lake drawdown periods via NSM and historic patterns.
Spatial and temporal patterns of N, P, and DO.
Environmental conditions causing these patterns.
Relationships between implementation of BMPs and nitrogen and phosphorus loads.
Nutrient absorption and retention capability of floodplain wetlands.
Causes of low summer and fall DO levels.
Effects of instream flow, other hydrologic characteristics, and tributary inflows on DO levels.
Relationships between reestablishment of physical habitat and hydrologic determinants and restoration of fish and wildlife resources.
Extent to which alternative restoration measures reestablish determinants of ecological integrity.
Ecologic responses to hydrologic restoration.
Relationship between supplemental management measures and fish and wildlife resources.
Conceptual and mathematical models of evaluation components, reference and baseline conditions.
Measurements of construction impacts, post-construction comparisons with reference and baseline conditions.
Assessment of supplemental resource management measures.

Figure 9. Goal, objectives, and information needs for Subregion 1.

EXISTING RESTORATION AND SCIENCE PLANS

Restoration Plans

The environmental impacts of channelization were quickly recognized, and opposition and calls for restoration of the river began before the Kissimmee River Flood Control Project was complete. Three major studies were conducted to evaluate restoration alternatives. The COE conducted two studies on the feasibility of restoring the Kissimmee (COE 1985, 1991) and the SFWMD (Loftin et al. 1990a) prepared a comparison of restoration strategies. The latter study contained a detailed analysis of hydrologic alternatives. The COE 1991 feasibility study and the SFWMD evaluation reached a similar conclusion: reestablishing a fully functional river and floodplain required recovery of the natural hydrologic regime. That could be done most effectively by backfilling a continuous section of C-38, connecting the remnant portions of the original river, and delivering water from the upper basin in a manner that mimics the natural system.

The Kissimmee River Restoration Project is the world's largest such effort and the first of its kind in the U.S. The restoration plan consists of two geographic components: the upper and lower basins. The restoration plan for the upper basin calls for regulation schedule modifications that provide a more natural downstream hydrology. Modification of S-65 is being considered and studied. Lakes Cypress, Hatchineha, Kissimmee, and Tiger will be impacted. Modification of canals that connect these lakes is under study, but the prevalent view is that major modifications will not be necessary.

The lower basin component consists of: backfilling 35 km (22 mi) of C-38 using dredged material that was disposed adjacent to the waterway during original construction; recarving 14 km (9 mi) of channel to reconnect remnant sections; removal of two water control structures; degrading floodplain levees; and backfilling borrow canals. The authorized restoration project stops short of full restoration in that S-65, S-65A, S-65D and S-65E will remain, as will the Pool A channel, Government Cut and Pool E. A 305-m (1000-ft) stretch of the canal was backfilled and completed in August 199[illegible] a test backfilling that enabled the COE and SFWMD to better predict environmental, engineering, and construction methodology likely to be encountered in future backfilling. This was successful, and an ongoing continuous monitoring of the test fill has provided valuable information that will lead to reduced cost and improved design. Canal backfilling is scheduled to begin in 1998, and construction will be completed around the year 2009.

Kissimmee River Research Plan

The SFWMD, in cooperation with the FGFWFC, an independent Scientific Advisory Panel (Karr et al. 1991), and the COE, developed the KRRP, which details the first 5 years of a $15.6-million monitoring and evaluation plan (SFWMD 1994). The primary focus of the plan is evaluation of restoration in the lower basin. Upper basin studies will focus primarily on expansion of littoral wetland communities on Lakes Kissimmee, Cypress, and Hatchineha. The KRRP is the basis for the scientific studies anticipated for restoration of the Kissimmee River and is appended to this chapter.

Goal

The overall goal of the KRRP is to measure the pulse of the restoration project, monitor construction impacts, measure the success of restoration, and allow adaptive management throughout the project's construction period. The size and life span of this project invites mid-course corrections as new information becomes available. The ability to conduct adaptive management will be largely accomplished by development of an understanding of ecosystem structure and function before and after restoration, demonstration of cause-and-effect relationship between restoration efforts and ecological responses, quantification of biological responses, and documentation of changes of social or scientific significance. In summary, the KRRP will provide information throughout the construction life of the project that will allow informed fine-tuning of the restoration process.

Approach

The KRRP adopted a six-phase implementation framework:

- **Conceptual Models.** Develop conceptual models that describe the ecological factors that govern wading bird, waterfowl, vegetation, fish, and invertebrate communities. These models will aid in understanding the effects of restoration and interpretation of the ecological evaluation program.

- **Reference Conditions.** Define reference conditions for impacted systems based on similar location, historical data or theoretical approaches. Reference conditions will apply to the selected plant and animal communities above, as well as hydrologic and water quality conditions. They will establish a level of performance against which actual results can be measured.

- **Baseline Conditions.** Existing conditions will be documented to establish a baseline. The baseline will be measured against actual restoration results and reference conditions as an expression of success.

- **Construction Impacts.** Water quality will be monitored during construction to rapidly recognize and correct problem areas and thereby minimize impacts of the restoration project. Water quality monitoring during the test fill placement provided valuable information and indicated construction could be accomplished without exceeding established criteria.

- **Evaluation.** The results of restoration will be measured in this phase. The initial opportunity for evaluation occurred in 1994, immediately after construction of the 305-m (1000-ft) test fill. Monitoring of the plug and borrow area began immediately after placement of the test fill and is ongoing.

- **Adaptive Management.** Adaptive management will be employed to update and fine-tune restoration activities.

INFORMATION NEEDS

The scientific information needs for Subregion 1 are outlined in the KRRP (attached appendix), which serves as the basis for the science studies needed in the Kissimmee River basin as part of the South Florida Ecosystem Restoration. The KRRP is built upon many previous studies and the findings of a Scientific Advisory Panel commissioned to develop a comprehensive ecological monitoring program.

Status of KRRP

The KRRP is in final draft form, and there has been significant progress in the first three phases of the approach.

- Conceptual models for aquatic invertebrates, fish, wading birds, and waterfowl have been completed and published in Dahm (1995). A conceptual model for vegetation is not yet available.

- Final reports on parameters for the reference conditions, as outlined in the KRRP, are expected by late 1996. Parameters for wading birds and waterfowl have been completed; other components are still under development.

- Proposals for collection of baseline data and monitoring the response to restoration activities have been fully developed; implementation has begun for invertebrates and fisheries. Plans for baseline studies for wading birds and waterfowl are being finalized; all will be initiated in 1996.

Construction-Related Monitoring

Restoration of the Kissimmee River basin presents several unique engineering, hydraulic and geotechnical features. Monitoring of these features will allow modification and improvements during the protracted period of construction and will provide answers to questions likely to arise in similar projects. Several aspects of this information will be useful in interpretation of ecological modeling results.

Hydraulic Models

Hydraulic resistance over the flood plain following restoration of wetland vegetation is a critical body of information needed to determine the upstream limit of backfilling and how the upper basin should be operated for flood control. The hydraulic monitoring program will measure this critical change in resistance and ultimately the final resistance of the restored flood plain.

Monitoring will be conducted at about 30 water-level and velocity vector points in the reach influenced by the first segment of backfilling. Monitoring gauges will be installed before reflooding to take advantage of dried flood plain conditions. Stilling wells will be installed such that the first 0.6 m (2 ft) of water table can be measured to allow monitoring of wetting and drying at the edge of the flood plain. Vertical control will be of extremely high order such that required precision in measuring water surface slope is not limited by precision of the level surveys. A local traverse can be used for control because relative precision between gauges within this network is much more important than global precision; however, this gauge network should be tied to overall basin water levels at prevailing level of precision.

Additional water level monitoring locations will be established in Lakes Kissimmee, Hatchineha, and Cypress in order to better manage operations in that sub-basin. More gauge locations will avoid existing problems with wind setup in the lakes, which can cause erroneous estimates of average lake stage. Lake regulation schedules are based on stages of hypothetically flat lake surfaces; therefore, average lake stages are preferable for use in daily operations.

Other hydrologic monitoring ongoing in the basin will continue. Rainfall gauges presently located at S-65 structures due to be destroyed will be relocated.

Sedimentation monitoring

Because of the uniqueness of this construction project, many of the determinations made regarding sedimentation issues have not been site proven in similar settings. The program will begin prior to construction in order to gather baseline data and will continue until such time as it can be established that the components of the project are stable.

The sediment monitoring program will be designed to include assessment of localized erosion and deposition at backfilled sections, river-canal junctions, and shallowed sections. Final graded and revegetated reaches of any completely backfilled canal reaches also will be monitored. The program also will monitor the stability of banks and bed of the river channels, especially any new river channels excavated to connect remnant river channels. Overall monitoring of the project area will be conducted so that any mass transport to Lake Okeechobee can be detected.

This program will include monitoring of suspended sediments and bed loads at a range of discharge conditions to assure that gradually developing problems with sediment and erosion control, if they occur, do not go undetected and lead to greater or catastrophic problems. In case any do occur, technical analyses and solution approaches will have site-specific data.

Stability monitoring

While the constructed features of this project will be subjected to normal inspections, including quality assurance/quality control and "as-built" comparisons to specifications, long-term monitoring is desirable for some

of the features. Features normally submerged and subjected to erosional forces will be monitored to determine stability. Concerns include armoring, unprotected soil in abutment areas, and gross stability of slopes and structural mass. Also, revegetated areas will be monitored for survivability of plants and overall coverage for erosion protection.

BIBLIOGRAPHY

Carroll, J.D., and A. Banner. 1991. Kissimmee River Restoration Project. Fish and Wildlife Coordination Act report. FWS, Vero Beach, Florida.

Dahm, C., editor. 1995. Special issue: Kissimmee River restoration. Restoration Ecology 3(3):145-238.

David, P.G. 1991. Environmental assessment of McArthur Ranch. Technical Memorandum 90-91 C. SFWMD, West Palm Beach, Florida.

Gunsalus, B., E.G. Flaig, and G. Ritter. 1992. Effectiveness of agricultural best management practices implemented in the Taylor Creek/Nubbin Slough Watershed and the Lower Kissimmee River Basin. SFWMD, West Palm Beach, Florida.

Karr, J.R., S. Heinz, A.C. Benke, R.E. Sparks, M.W. Weller, J.V. McArthur, and J.H. Zar. 1991. Design of a restoration evaluation program. Report of The Scientific Advisory Panel on Environmental Monitoring of the Kissimmee River Restoration to SFWMD, West Palm Beach, Florida.

Loftin, M.K., L.A. Toth, and J.T.B. Obeysekera. 1990a. Kissimmee River Restoration: alternative plan evaluation and preliminary design report. SFWMD, West Palm Beach, Florida.

Loftin, M.K.; L.A. Toth, and J.T.B. Obeysekera. 1990b. Proceedings Kissimmee River Restoration Symposium. Orlando, Florida, October 17-20, 1988. SFWMD, West Palm Beach, Florida.

Miller, S.J., G.L. Warren, M.J. Vogel, J.G. Wullschleger, and L.J. Davis. 1990. Lake Okeechobee-Kissimmee River-Everglades resource evaluation project. FGFWFC, Okeechobee, Florida.

Perrin, L.S., M.F. Allen, L.A. Rowse, F. Montalbano III, K.J. Foote, and M.W. Olinde. 1982. A report on fish and wildlife studies in the Kissimmee River basin and recommendations for restoration. Office of Environmental Services, FGFWFC, Okeechobee, Florida.

Pfeuffer, R.J. 1990. Herbicide monitoring program for N-methylformamide and fluridone [Sonar(R)]. SFWMD, West Palm Beach, Florida.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

South Florida Water Management District. 1994. Draft Kissimmee River Research Plan. SFWMD, West Palm Beach, Florida.

Toland, B.R. 1990. Effects of the Kissimmee River Pool B restoration demonstration project on wading birds and waterfowl, 1987-1989. FGFWFC, Vero Beach, Florida.

Toth, L.A. 1991. Environmental responses to the Kissimmee River Demonstration Project. SFWMD, West Palm Beach, Florida.

Toth, L.A. 1992. Principles and guidelines for restoration of river/floodplain ecosystems - Kissimmee River, Florida. SFWMD, West Palm Beach, Florida.

Toth, L.A. 1993. The ecological basis of the Kissimmee River restoration plan. Florida Scientist 56(1):25-51.

Toth, L.A., and N.G. Aumen. 1993. Integration of multiple issues in environmental restoration and resource enhancements projects in south central Florida. SFWMD, West Palm Beach, Florida.

Toth, L.A., J.T.B. Obeysekera, W.A. Perkins, and M.K. Loftin. 1993. Flow regulation and restoration of Florida's Kissimmee River. Regulated Rivers: Research & Management 8:155-166.

U.S. Army Corps of Engineers. 1985. Central and Southern Florida, Kissimmee River, Florida. Final Feasibility Report and Environmental Impact Statement. COE, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1991. Central and Southern Florida, Kissimmee River, Florida. Final Feasibility Report and Environmental Impact Statement, Central and Southern Florida Project. COE, Jacksonville, Florida.

U.S. Fish and Wildlife Service. 1958. A detailed report of the fish and wildlife resources in relation to the Corps of Engineers' plan of development, Kissimmee River Basin, Florida. FWS, Vero Beach, Florida.

APPENDIX

July 1994

KISSIMMEE RIVER RESEARCH PLAN

SUMMARY

This five-year research plan outlines and describes research that will be used to evaluate the initial phase of the Kissimmee River ecosystem restoration. The overall goal of the restoration evaluation will be to determine the direction and extent of the recovery of the Kissimmee River-floodplain ecosystem from established baseline condition as compared to an historically-based reference condition. The success of this early phase of the restoration will be judged by recovery of ecosystem processes and the biological communities they support. Thus, the evaluation program will have an ecosystem perspective, with an experimental, hypothesis-driven approach supported by empirical data collection on the status of, and trends in, key ecosystem components. These key channel and floodplain components are: geomorphology, hydrology, water quality, and producer (river and floodplain vascular plant communities) and consumer (invertebrates, fish, and wading and water birds) organisms.

Conceptual models, encompassing the best documented historical reference condition, the channelized condition, and the proposed restored condition of the most important system structure and processes, will be developed for the river ecosystem as a whole and for each of the ecosystem sub-components. The five-year Kissimmee River Research Plan has been developed to achieve these evaluation goals. The fundamental elements of the Kissimmee River Research Plan are summarized below.

1. **Advisory Panel.** An external Advisory Panel will review and provide guidance on all components of the research plan as well as the formal cost-sharing collaborative efforts between the SFWMD and the U. S. Army Corps of Engineers. In addition, the Panel will review the related research plans of the Florida Game and Freshwater Fish Commission, and explore proposed collaborative research efforts with the U. S. Geological Survey and other agencies and institutions as needed.

2. **Conceptual Models.** Conceptual models will be developed for ecosystem dynamics and the structure and function of key ecosystem components. A select panel of authors will prepare papers presenting models for geomorphic/vegetational, invertebrate, fish and bird components of the Kissimmee River-floodplain, as well as papers presenting an historical perspective of the restoration and summarizing and synthesizing the overall objectives for evaluating ecosystem recovery.

3. **Remote Sensing/GIS Evaluation.** Remote sensing and GIS (Geographic Information System) procedures for spatial and temporal evaluation of river and floodplain habitats will be developed and implemented. This approach is essential as the only cost-effective means of documenting landscape level changes.

4. **Baseline Conditions.** Baseline conditions for pre-restoration evaluation of whole ecosystem and ecosystem component responses will be established. Baseline conditions prior to initiation of the restoration will be the condition to which the recovering system will be compared.

5. **Reference Conditions.** Reference conditions will be defined for the Kissimmee River / floodplain ecosystem and for selected ecosystem components to which baseline system structure and function can be compared during the course of the restoration.

6. **Impact Assessment.** Water quality changes associated with the pilot test fill project will be monitored. These data will be used to predict effects of the full-scale restoration on water quality of the river. A modeling component of this phase will allow predictive simulation of the hydrologic events that would result in different water quality conditions.

7. **Headwaters Revitalization Influences.** The main emphasis will be on modifications of hydrologic regimes that influence littoral and wetland areas in the headwater lakes region. Responses by avian components to the modified hydrologic regime and wetland habitat will be evaluated in the context of whole ecosystem restoration. Computer modeling will be used to evaluate flood control and operation schedules for lakes in the headwaters area as a means of providing the necessary inflows to the Kissimmee River to achieve the desired recovery.

8. **Experimental / Statistical Design and Analysis.** Empirical data collection methods and the design of experiments to evaluate the success of the restoration project in re-establishing ecosystem integrity, including plant and wildlife values, in the Kissimmee River system will be developed. These will be referenced to the conceptual models (2) and incorporate evaluations of reference and baseline conditions. The statistical procedures will be applied to study components 3-7 above. Of special concern are procedures to evaluate trends in recovery during the course of the restoration relative to established baseline conditions and presumably moving toward the proposed reference conditions.

Scheduling. Timing of the whole ecosystem and ecosystem components evaluation program will be referenced to three construction activities that constitute the restoration project:

1) backfilling of a 300 meter test reach of canal in April-August of 1994;
2) initiation of the Headwaters Revitalization Program in 1996; and
3) initiation of the first phase of the full-scale backfilling of the canal in 1998.

The whole ecosystem and ecosystem components evaluation program will be phased to insure that adequate conceptual models and remote sensing/GIS procedures have been developed, and that baseline and reference condition benchmarks have been established prior to the initiation of the full-scale backfilling of the canal in 1998. Data on wading birds will be gathered prior to initiation of the Headwaters Revitalization Program in 1995.

Products. The research staff will actively participate in future planning for adaptive management of the restoration project. Also, the staff will be involved in the publication of restoration-related, peer-reviewed scientific papers to document the on-going effects of the restoration on recovery of the river-floodplain ecosystem toward the proposed reference condition.

A chronology of milestones for the Kissimmee River Restoration Project from the Congressional authorization of the Kissimmee River Flood Control Project in 1954 through the presently on-going test fill (initiated in April, 1994) is given in **Fig. 1.** The chronology is plotted against funding levels over the time period. The Kissimmee River Research Plan is presented in the form of an hierarchical Decision Analysis Support System in **Fig. 2.** Management goals and objectives, research objectives, attributes, and information needs are summarized for the planned research. A flow chart of research questions which derives from the Decision Analysis Support System is shown in **Fig. 3.** The three basic questions addressed are 1) what were the historical reference ecosystem conditions to which the restoration should be compared? 2) what were the baseline conditions after completion of channelization? 3) what are the status and trends in the recovery of habitat structure and ecosystem processes, and the biological communities they support, in the restored section of the Kissimmee River-floodplain?

A Resource Summary Utilization Chart (GANTT) giving task descriptions and the Kissimmee River Restoration Project are summarized in **Table 1** beginning with water quality evaluations in 1971 through present recommendations on the evaluation program.

INTRODUCTION

Environmental resources of the Kissimmee River basin have been studied for over 40 years. The primary impetus for these efforts has been the Central and Southern Florida Flood Control Project, which resulted in channelization of the river. Studies documenting the ecological impacts of channelization and evaluations of the utility of various restoration measures began in the early 1970s. These studies initially had two somewhat independent areas of emphasis. One line of investigation dealt with water quality issues and the value of Kissimmee River restoration as a means to prevent or reverse accelerated eutrophication of Lake Okeechobee. Other studies focused on the impacts to and restoration of biological resources in the Kissimmee River valley.

At least part of the early impetus for restoration was derived from concern that channelization of the river had bypassed nutrient absorption processes on the floodplain and thereby created a conduit for rapid downstream transport of nutrient loads into Lake Okeechobee. Although early restoration-related studies identified agricultural runoff, particularly from improved pasture and dairy operations, and associated secondary drainage systems, as the primary causes of elevated nutrient loads in the channelized system, the nutrient removal capabilities of Kissimmee floodplain marshes also were verified. However, these studies indicated that re-establishment of the nutrient filtration function would be effective only if hydrologic characteristics of the former floodplain wetlands are restored and elevated nutrient inputs generated by intensive agricultural land uses are reduced at their source. Subsequently, low summer and fall dissolved oxygen regimes were identified as the primary water quality related problem, and a principal cause of deterioration of biological communities in the channelized system.

Channelization replaced the meandering river with a 90 km long, 9 m deep and 64-105 m wide canal (C-38), which, along with its water control structures, transformed the contiguous river/floodplain ecosystem into a series of five impoundments (pools A through E). The excavation of C-38 and deposition of spoil obliterated 56 km of river channel and 2800 ha of floodplain, and water levels were stabilized at stages that completely drained the floodplain in the upper two-thirds of each pool. In the absence of flow, thick deposits of organic matter accumulated on the bottom of the remaining river channel, and reduced depth and substrate diversity within these stagnant, remnant river courses.

These physical impacts led to significant changes in the functional characteristics of biological and chemical components of the river-floodplain ecosystem. In addition to the wetlands that were destroyed by the canal and spoil, at least 12,000 ha of the floodplain wetland mosaic were replaced by broad expanses of relatively homogenous unimproved and improved pasture communities. Elimination of floodplain wetlands and stabilization of water levels within the remaining impounded wetlands led to a 74% decrease in the number of active Bald eagle (*Haliaeetus leucocephalus leucocephalus*) territories and 92% reduction in wintering waterfowl. The diverse community of wading birds that formerly utilized the floodplain has been replaced by dominant populations of the naturalized cattle egret (*Bubulcus ibis*), a species that occurs primarily in association with cattle on pasture and other ruderal, upland habitats. Drainage of wetlands also virtually destroyed the floodplain food web, including a constant source of over five billion forage fish and six billion freshwater shrimp.

Other biological impacts occurred as a result of habitat alteration and degradation associated with the transformation of the river into a series of impoundments. Benthic invertebrate communities in the canal and remaining river runs display low densities and diversity and are dominated by larval phantom midges (*Chaoborus punctipennis*), a species which is characteristic of a lentic rather than riverine environments. Fish species richness in remnant river habitats has declined from 39 to 17 species; two species have been extirpated and game fish populations appear to be undergoing a continuous, long-term decline.

The adoption of an holistic ecosystem restoration goal - re-establishment of ecological integrity - was a pivotal event in the restoration planning process. This ecosystem perspective emanated from a 1988 symposium on the restoration initiative. Components of ecological integrity include the magnitude and rate of Kissimmee River-floodplain ecosystem processes (e.g., autotrophy/heterotrophy balance and concentration and turnover rates of phosphorous and nitrogen). In addition, the diversity, density and production of key communities, littoral and floodplain vegetation, invertebrates, fish, and birds, will be used as specific measures of the ecological integrity of the restored Kissimmee River-floodplain ecosystem. The overall approach will allow both general system trends and specific populations of interest to be followed through the recovery process.

Establishment of the goal to restore ecological integrity led to the development of a comprehensive set of restoration guidelines and criteria. These guidelines and criteria were founded upon the geomorphic and hydrologic determinants of ecosystem integrity that had been altered by channelization and other aspects of the flood control project and they provided a rigorous and objective basis for the analysis of alternative restoration plans. Available data on pre-channelization resources, impacts of channelization, and restoration-related studies were integrated. This led to the development and adoption of the current plan to restore the ecological integrity of the Kissimmee River-floodplain ecosystem. This plan consists of two integrated components: The lower basin component, that will restore the physical form of the river and floodplain, and the headwaters revitalization component, that will modify regulation of the hydrologic regime of the river so as to establish discharge regimes comparable to historic conditions

The lower basin plan consists of:

1. backfilling 35 km of canal using the adjacent dredged spoil material from the original canal excavation for fill;

2. re-carving 14 km of river channel to reconnect remnant river channels in areas where the excavation of C-38 or placement of excavated material obliterated former river channel;

3. removal of two of the water control structures and their tieback levees; and

4. degradation of other floodplain levees or berms and backfilling of the borrow canals for these levees and secondary drainage canals within the floodplain.

The headwater revitalization plan will re-establish inflow characteristics that are necessary to restore the hydrologic determinants of ecosystem integrity. Inflow characteristics will be determined through evaluation of alternative flood control and operation schedules for lakes in the headwaters region with the objective of providing the necessary inflows to the Kissimmee River to achieve the desired recovery. Evaluations will be conducted with the Upper Kissimmee Chain of Lakes Model (UKISS), a computer simulation of the movement of water through the upper chain of lakes.

The 1992 Water Resources Development Act authorized restoration construction and a federal-state, cost-sharing partnership for its implementation. A pilot test fill project began in April 1994 and the initiation of the headwaters component is expected to begin in 1996. The first phase of canal backfilling is scheduled to start in 1998. Construction will take approximately 15 years to complete.

The Kissimmee River Research Plan describes research framed under this federal-state Kissimmee River restoration partnership authorized in the 1992 Water Resources Development Act (Public Law 102-580). The authorized plan, described in the U. S. Army Corps of Engineers 1991 Feasibility Study, includes approximately $15 million for a ***comprehensive ecological evaluation program*** for the restoration project. The ecological research to be conducted under the Kissimmee River Research Plan involves a cost-sharing Project Cooperative Agreement (PCA) with the U. S. Army Corps of Engineers, personnel from the Kissimmee & Okeechobee Systems Research and the Research Appraisal Divisions, and collaborative work with the Florida Game and Freshwater Fish Commission (FGFWFC).

Although a broad array of environmental impacts has driven the restoration initiative and adoption of the restoration plan, the challenge is to develop strategy for evaluating the success of the recovery. Studies that preceded development of the river restoration plan, relied on measures of select resource values (e.g., wetlands, game fish, waterfowl, wading birds, and water quality) as independent objectives. Further, evaluations of alternative restoration measures targeted river and floodplain resources and functions as if they were independent variables.

Within the overall management goal of the Kissimmee River Research Plan, to evaluate the restoration of ecological integrity of the Kissimmee River and its flood plain, there are three general objectives to facilitate implementation of the restoration effort:

1) Provide continual scientific input and support for the detailed design phases of both the headwaters revitalization and lower basin components of the restoration project;

2) Develop, coordinate, implement, and integrate an ecological evaluation program for the restoration project that operates in an adaptive management mode (e.g., as new data allow revision of conceptual models, these revisions will be adapted into the physical restoration process whenever possible);

3) Disseminate restoration-related information through peer-reviewed scientific publications and presentations at professional and technical conferences. A critical facet of this information exchange will be to continually relate the research findings to the overall objectives of the Kissimmee River-floodplain restoration.

The ecological evaluation program will be the cornerstone of research activities provided by this five year plan. The implementation plan that follows provides details for the proposed restoration evaluation program, including details of initial study phases. Annual updates and modifications of the restoration evaluation program and study design details will be continued throughout the 15-year restoration construction period.

SECTION I

IMPLEMENTATION PLAN FOR THE KISSIMMEE RIVER RESTORATION EVALUATION PROGRAM

1.1 Conceptual/Empirical Goals of the Ecological Evaluation Program

The ecological evaluation program is designed to assess effects of the restoration project and will have four conceptual goals:

1) Provide a thorough understanding of river-floodplain ecosystem structure and function in the historical reference condition, and pre- and post-restoration condition;

2) Identify and measure quantifiable ecological responses using observational and hypothesis-driven experimental approaches;

3) Show direct cause and effect relationships between the physical restoration and ecological responses;

4) Document ecological changes resulting from the restoration that are of scientific (e.g., rates of ecosystem processes and community structure) and social importance (e.g., nutrient assimilative capacity, increases in game fish and wading bird populations).

1.2 Background

In 1991, a District-commissioned Scientific Advisory Panel, with technical input from the U.S. Army Corps of Engineers, U.S. Fish and Wildlife Service, Florida Department of Environmental Regulation, Florida Game and Fresh Water Fish Commission, Florida Department of Natural Resources, St. John's River Water Management District and the South Florida Water Management District, provided recommendations for the design of the lower basin restoration evaluation program. These recommendations included prioritized evaluation components and a five-phase framework for implementation.

The 1992 Water Resources Development Act authorizes construction of both the upper and lower Kissimmee basin components of the Kissimmee River ecosystem restoration plan. The South Florida Water Management District has agreed to enter into a 50/50 cost-sharing agreement with the U.S. Army Corps of Engineers to complete the restoration project, which includes environmental monitoring of the upper basin component and a comprehensive ecological evaluation program for the lower basin.

In 1993, the district commissioned a set of conceptual model papers on predicted ecological conditions that will result from the restoration. A series of papers has been prepared and will be submitted to the Journal of Restoration Ecology in 1994. The papers include: an introduction and overview, geomorphology/vegetation, invertebrates, fish, birds, and a synthesis.

1.3 Purpose

The purpose of this research program is to document and evaluate ecological responses to the ecosystem restoration plan and provide for continuous, scientifically informed fine-tuning of restoration efforts.

SECTION II

PROJECT DESCRIPTION

The ecosystem restoration evaluation program, will evaluate ecosystem processes and the diversity, density and production of key communities (e.g., vascular plants, fish, and water and wading birds). Because the headwaters component of the project is being conducted to achieve the goal of restoring the ecological integrity of the lower basin ecosystem, the primary focus of the evaluation program will be on the river- floodplain ecosystem in the lower basin. The limited upper basin evaluation program will focus on the expansion of littoral wetland communities and predicted responses by wading birds and waterfowl along Lakes Kissimmee, Cypress and Hatchineha. Use of the UKISS computer model to evaluate flood control and operation schedules for the upper basin will take into account the goal of establishing and maintaining expanded wetlands.

Based upon recommendations of the Scientific Advisory Panel and subsequent input from state and federal agencies, the District has initiated a comprehensive restoration evaluation program. The approach includes measurements of whole ecosystem response in the form of an autotrophy/heterotrophy index as well as estimates of diversity, density and production estimates of selected vascular plant, invertebrate, fish, and bird species. Special attention will be given to endangered species. Changes in principal habitat components also will be measured. These will include hydrologic characteristics, water quality and nutrient cycling, and river channel and floodplain geomorphic parameters along the river channel. As part of the measurements of the autotrophic/heterotrophic index, general dissolved oxygen regimes will be monitored in the river channel, the littoral zone of the river, and the wetland floodplain habitats.

A foundation for all the research in the lower basin and wetland studies in the upper basin will be provided by routine annual, low elevation remote sensing. A GIS will be developed with primary data layers for elevation, hydrology, hydro-soils, and vascular plant communities. Additional data layers will be created for channel and floodplain geomorphic features (e.g., large woody debris, channel braids and islands) and for the distribution of key animal communities (invertebrates, fish, birds).

2.1 Lower Basin Ecological Evaluation Program Components

2.1.1 Hydrology

Hydrologic studies will determine if restoration measures are successful in re-establishing the key hydrologic determinants of ecological integrity of the Kissimmee River-floodplain ecosystem. The results of the hydrologic analyses will be stored as a primary data layer, interfaced with an elevation contour data layer, in GIS format. This will provide the basis for evaluating the relationship between hydrology and the distribution of vascular plant communities (and other biological data layers) in the channel and on the floodplain and for recommendations about modifications in water release and storage operations for the Upper Basin. This "adaptive management " strategy will be followed throughout the duration of the restoration project.

Associated monitoring of the hydraulic resistance over the restored floodplain, and thus the pattern of water retention and flow, is needed to determine the upstream limit of backfilling.

2.1.2 Channel and Floodplain Geomorphology and Sediments

Evaluations of river channel and floodplain geomorphology including sediment distribution and characteristics will be made. Special attention will be directed to large woody debris (LWD) in the channel and on the wetlands and the potential for future inputs of LWD, will be determined by annual remote sensing and the information used to create a geomorphic data layer in the GIS. The presence and potential for development of braids and islands also will be mapped annually and data added to the geomorphic layer. The restored river channel, particularly excavated channels, will be analyzed for localized erosion, deposition and stability.

2.1.3 River-floodplain Metabolism

River-floodplain metabolism (autotrophy/heterotrophy index or P/R) will be measured seasonally in an extensive fashion - that is, over many habitats or portions of habitats. Evaluations, to be determined in specially designed metabolism chambers, will be made over 24 hour periods seasonally and the results entered as a data layer in the GIS system referenced to the distribution of vegetation communities (see below).

2.1.4 Vegetation Communities

Littoral and floodplain vegetation will be used as the primary biological structural template in the GIS system. The vegetation, divided into at least six basic community types: submergent, floating, and emergent littoral communities and broad leaf marsh, wetland shrub, and wet prairie floodplain communities. These will be mapped on to the physical data layers - elevation, hydrology, and geomorphology. Other biological data layers - invertebrates, fish, wading birds and waterfowl - will be mapped onto this vegetation template in the GIS system. The areal extent of each vascular plant community will be remotely sensed and put into the GIS format annually.

2.1.5 Invertebrates

Invertebrates are the second link (primary consumers) in the food web, provide food resources for secondary consumers, e.g. fish and water birds, and they are indicators of habitat conditions. Invertebrates can serve as good indicators of ecological integrity because they are readily collected and can integrate changes over large spatial and long temporal scales. Taxonomic studies of invertebrates will be supplemented with functional analyses that maximize ecological information per unit of taxonomic effort. The invertebrate data will form layers to overlay the vegetation communities in the GIS system on a seasonal basis. Production estimates will be made for one or more selected species.

2.1.6 Fish

Fish will be evaluated because they are valued by society for sport and food, and their abundance and health affect and reflect conditions in the river-floodplain ecosystem. The fish community is relatively diverse and forms, along with invertebrates, the major food base for aquatic birds. The fish data will form layers to overlay the littoral and floodplain vegetation communities in the GIS system. Production estimates for largemouth bass will be made.

2.1.7 Birds

Extensive studies of wading birds and waterfowl are needed because of their visibility (societal importance), and because they reflect different feeding guilds and are good indicators of the productivity and general health of the system. These studies will include special focus on evaluations of endangered species (i.e., bald eagle, wood stork and snail kite) responses. The bird data will form layers to overlay the vegetation communities in the GIS system on a seasonal basis. Recruitment rates will be estimated for several selected species.

2.1.8 Water Quality

The highest priorities of water quality evaluations will involve assessments of construction-related impacts and dissolved oxygen dynamics. Construction impact assessments of water quality will be made (e.g., suspended solids and turbidity) and steps taken as necessary to minimize impacts. Dissolved oxygen studies are required because of the limiting role this parameter exerts on biological communities in the channelized system. These measurements will be made routinely and in conjunction with the river-floodplain metabolism studies described above. Other water quality parameters that will be monitored include the chemical species of the nutrients phosphorus and nitrogen, and organic carbon (dissolved and particulate). Phosphorus and nitrogen are important because of their significance downstream in Lake Okeechobee where they have been linked to algal blooms and because of their role in regulating biological turnover rates in the river-floodplain ecosystem. Because the energy base of the restored ecosystem will change during restoration, evaluations of changes in the quality and quantity of organic matter (carbon) transported through the ecosystem is central to understanding the limits and opportunities in system management.

SECTION III

DESCRIPTION OF TASKS

3.1 Development of Conceptual Models

A set of conceptual models has been developed for each ecosystem evaluation component. These models describe the ecological processes and variables that govern river channel geomorphology and the structure and functioning of vascular plant, invertebrate, fish, and wading bird and waterfowl communities. The conceptual models will facilitate understanding of the effects of restoration on ecosystem and landscape pattern and process by describing expected conditions following recovery. The will be used also to insure adequate design of the restoration research plans and as an aid for interpretation of results of the ecological evaluation program.

3.2 GIS

The primary data layers of the GIS system will be elevation, hydrology, hydro-soils, and the areal extent of vascular plant communities. These will serve as a template on to which the recovery response of the invertebrate, fish, and bird communities will be mapped.

3.3 Establishing Reference and Baseline Conditions

The rationale, methods, and schedule for defining reference and baseline conditions for the ecological components of the restoration evaluation program are described below. Because no suitable reference sites have been located in the Kissimmee River basin, of necessity the reference conditions will be general in nature and based on the historical record for the Kissimmee River system, the applicable published literature including studies on other southeast Atlantic coastal systems. A major portion of the literature perspective has been reviewed in the conceptual model papers that will appear in the Journal of Restoration Ecology.

3.3.1 Reference Conditions

Reference conditions will be established based on the historical record leading to expectations for each ecosystem evaluation component. Remnant river channel-floodplain habitats, historical records covering pre-channelization and pre-settlement conditions, data from sites on similar rivers in the southeast, and the published literature on similar rivers all will be used to define reference conditions. The District is negotiating a contract with Drs. Sedell (Oregon State University) and Burnett (Florida Atlantic University) to review and summarize the historical record of the Kissimmee River channel and floodplain geomorphology, and vegetation. The expectations for recovery, as described in the conceptual model papers on the Kissimmee River-floodplain ecosystem and component selected biological communities, will serve as the general theoretical basis for defining reference conditions. Once target reference conditions are defined, sampling will be designed to incorporate the expectation of long-term variability patterns in the reference conditions recorded in the literature and from other lower east coast river systems. An asymmetrical sampling protocol, with a large number of reference site samples compared to single samples from pre-and post-restoration habitats, will be employed to concentrate the analytical power on the effects of the restoration distinguished from natural variation.

Because the restoration project will be constructed in phases, reference conditions must have a spatial and temporal aspect that will allow for continuous evaluation and tracking of restoration success during and after the construction period. Also, it is necessary to differentiate between short and long-term restoration responses, and to account for the variability in population and community structure that likely occurred in the historical system (which approaches as closely as possible pre-settlement conditions of channel geomorphology) and consequently is to be expected in the restored ecosystem as well.

The hydrological historical database includes 16-30 years of discharge data at three locations along the river and 25-37 years of stage height data at four river locations. These data provided the basis for the criteria that were used as the pre-channelization hydrologic determinants of ecological integrity and to select the restoration plan. The

hydrologic reference conditions for the restoration project will be based on the pre-channelization criteria with particular attention paid to data on temporal flow patterns from the earliest possible records.

No historical data on the river littoral vegetation communities have been located. However, historical aerial photographs will be used to quantify the area covered by vegetation in the channel and the floodplain whenever possible, and possibly to differentiate the types of littoral vegetation communities that occurred along the pre-channelization river channel. The initial data set will constitute baseline conditions.

Maps of pre-channelization floodplain vegetation community distributions have been constructed from analyses of historic (1952-54) aerial photographs (Pierce et al., 1982). Assuming the same historic spatial distribution of plant communities will be re-established following restoration of historic hydrologic characteristics, these maps provide a basis for floodplain vegetation reference conditions before channel construction, but probably not for pre-settlement conditions. The demonstration project, in which a portion of the remnant river channel was flooded, confirmed that vegetation will likely recover to the general condition represented in the 1952-54 analyses. Existing interpretations of the photographic information provide only broad distribution patterns of major plant community types and further analyses will concentrate on more precisely defining and characterizing the distributional mosaic of habitat patches along and across the floodplain. Additionally, some adjustments and refinements to the pre-canal (1952-54) conditions are needed. For example, floodplain habitats that were formerly dominated by woody species and were cleared after the floodplain was drained, or in the century after settlement, cannot be expected to return in the short term. Re-establishment of the floodplain forest, and the supply of large woody debris to the channel, will require a long term plan and undoubtedly involve specific plantings.

There are no published historical data on invertebrate communities of the Kissimmee River. The reference condition will be based on the general expectations outlined in the conceptual model papers being published in the Journal of Restoration Ecology. Specifics will come from collection and analysis of remnant river-floodplain habitats and the restoration project area of the Kissimmee River and upon published data on invertebrate communities of other similar, but un-impacted river systems within the Southern Coastal Plain ecological region of Florida. It may be necessary to utilize other Lower Coastal Plain rivers of Florida, Alabama, Georgia, North Carolina and South Carolina for reference site information. Additional insight into historical reference conditions will come from a search of invertebrate collections at Florida universities and state agencies, and the Smithsonian Institution.

One set of historical data on fish communities in various river and floodplain habitats of the Kissimmee River was collected between 1955-57 by the Florida Game and Fresh Water Fish Commission. Although a variety of methods was employed, gear selectivity and lack of information on spatial and temporal variability precludes a comprehensive quantitative characterization of historic fish community structure from these data. Reference conditions for fish communities, reflecting the expected recovery characteristics as detailed in the conceptual model papers being published in the Journal of Restoration Ecology, will be defined and sampling of fish populations will be aimed at evaluating whether population changes approach the expected reference conditions.

In the case of fish populations, there is a need to include measurements of taxonomic composition, diversity, abundance, the presence of indicator and exotic taxa, recruitment dynamics, and river channel and floodplain habitat utilization, including any differentiation among life history stages (e.g., feeding, reproduction, refuge, etc.). Also, similar to the invertebrate studies, characteristics of the reference condition will be defined using data from the literature and from other lower coastal rivers that are most natural (i. e. most closely reflect some attributes of the historical condition).

Wading birds and waterfowl populations will be evaluated in Kissimmee River littoral and floodplain habitats. Draft manuscripts on wading bird and waterfowl reference conditions have been prepared and are under review. Information on composition and relative abundances of wading bird species that utilized the historic river and floodplain are provided by Perrin et al. (1982) and in unpublished Audubon reports dating back to the 1930s. The Audubon reports provide some quantitative data but are based upon inconsistent or undefined censusing methods. Realistic expectations for restoration of wading bird communities must reflect the impacts that have affected populations of these species throughout the south/central Florida landscape. Reference conditions for wading birds will include expectations for population densities of selected species and/or guilds, establishment of rookeries and other breeding sites, and other habitat-based projections as characterized in the conceptual model paper to be

published in the Journal of Restoration Ecology and upon published Audubon reports on habitat utilization by the various species that occur in the Kissimmee River basin.

Quantitative historical data on wintering waterfowl populations on the Kissimmee River floodplain were collected between 1949-57 by the U.S Fish and Wildlife Service and Florida Game and Fresh Water Fish Commission. Although about 50% of the primary habitat (wet prairie) utilized by wintering waterfowl in the historic Kissimmee River-floodplain system will be restored, expectations for waterfowl, like wading birds, must reflect the impacts that extraneous factors have had on both regional and migratory waterfowl populations.

No pre-channelization water chemistry data have been located. The principal parameters requiring reference conditions are dissolved oxygen, inorganic and organic nitrogen and phosphorus concentrations, and possibly organic carbon fractions. Expectations for dissolved oxygen regimes will be determined. Nutrients and organic carbon dynamics, including coarse, fine particulate, and dissolved organic matter, will be based on published data from other similar river systems in the southeastern United States.

3.3.2 Baseline Conditions

Baseline, that is existing conditions, will be documented for comparison with the reference conditions as the recovery of the river-floodplain system proceeds. Ultimately the baseline conditions will be compared to the actual conditions achieved by the restoration. These studies will be consistent with the conceptual models and reference condition measurements that are established for each evaluation component. Baseline studies will be centered in Pool C (the area that will be affected by the first phase of restoration) and will include control sites in other pools. At least two years of pre-construction baseline data will be collected for all components and remotely sensed data on the physical (contour, hydrology) and biological patterns (landscape coverage of vegetational communities) will serve as the basic underlying data layers in GIS analysis.

Baseline studies for evaluating environmental benefits in the headwater lakes, that is, the Headwaters Revitalization Component, will focus primarily on the expansion of littoral wetland communities and wading bird and waterfowl utilization, as documented through remote sensing.

The river channel and flood plain will be surveyed annually by low elevation over flight remote sensing and a GIS database prepared and periodically updated geomorphic features (e.g., meanders, braids, large woody debris, and off-channel areas) will be mapped onto a contour data layer. In addition, the aerial extent of the three most abundant floodplain plant community types and the three channel plant associations will be digitized and entered into a GIS format. If possible, color infrared aerial photos will be used. These would be scanned and hand checked for accuracy and the extent of coverage of the major plant associations groundtruthed at selected locations. The initial data set will constitute baseline conditions.

River-floodplain metabolism (autotrophy/heterotrophy index or P/R) will be measured seasonally in 24 hour experiments in replicated, randomly selected habitats in the river channel and on the floodplain. Paired metabolism measurement units (each unit consisting of three replicate chambers) will be used to characterize the P/R in a given habitat simultaneously at two locations. The sampling strategy will allow evaluation of the variation between the same habitat type at two different locations under the same light and temperature regimes. Evaluations of P/R will be made seasonally of the representative river and floodplain habitats and the results entered as a data layer in the GIS system referenced to the distribution of vegetation communities (see below). The initial data set will constitute baseline conditions.

River and floodplain plant communities (primarily submerged, floating, and emergent littoral and broad leaf marsh, wetland shrub, and wet prairie communities) will be evaluated annually on an aerial basis using remote sensing and the information will form a data layer in the GIS system.

Measurements of invertebrate communities will concentrate on documenting the taxonomic composition and abundance of the associations of the key river and floodplain habitats. Functional analyses, both feeding and habit (attachment, locomotion, and concealment) functional groups also will be characterized. The District has approved a contract with Dr. Richard Merritt of Michigan State University for evaluation of functional groups in the

Kissimmee River-floodplain system. Data on invertebrate community parameters collected for the base line conditions before channel filling and in the first five years of the restoration will be compared to the reference condition - that is the expected recovery characteristics as defined in the conceptual model paper to be published in the Journal of Restoration Ecology.

Fish sampling will be accomplished in collaboration with the Florida Game and Fresh Water Fish Commission. Sampling will involve the use of traps, seines, and electro-fishing gear. The District will be the overall manager of the design of methods for fish collection and analysis.

Baseline conditions will be based on on-going bird census data which will be followed up by additional collaborative studies with the Florida Game and Freshwater fish commission. Comparisons between baseline and recovery conditions will target specific reference predictions such as increased usage of the floodplain, specifically the re-established wet prairie habitat, by resident mottled ducks and migratory dabbling ducks. As in the case of plants, invertebrates, and fish, the bird information will form a layer in the GIS database.

The full suite of water quality parameters that are being routinely measured constitute the baseline condition. These will continue to be measured as the restoration proceeds and compared against the reconstructed (hypothesized) reference conditions.

3.4 Construction Impact Monitoring

Assessments of construction impacts will ensure that temporary or incidental environmental changes are documented so that the effects of the construction can be discerned and, therefore, minimized over the planned 15-year construction period. An early indication of potential construction impacts will be provided through environmental studies associated with the pilot "test fill" project. This test project began in April 1994 and will backfill 300 m of canal and return 5.2 ha of adjacent spoil to pre-canal floodplain elevations. The test-fill project is intended primarily to evaluate fill consolidation and construction methodology, but provides the opportunity for water quality assessments that will be used to develop the final restoration plan.

This phase of the work will be used in an adaptive management strategy to continually provide information on for fine-tuning the restoration project and associated land and water management components.

3.4.1 Test-Fill Evaluation Plan - Potential Impacts on Water Quality

The principal water quality concerns relating to the test-fill are turbidity, suspended solids transport, dissolved oxygen regimes, and to a lesser extent, nutrient export from re-suspended sediments. Core borings indicate that the spoil mound that will serve as the source of backfill material consists primarily of coarse sand and shell with a small clay component. Due to the canal's hydraulics (i.e., capacity to carry high discharges at low velocities) the potential for sediment transport in the canal is extremely low. Consequently, most suspended backfill material is expected to quickly settle, although suspension of the clay component could result in high localized turbidity levels in the vicinity of the backfilled reach.

Low dissolved oxygen concentrations are the principal water quality problem within the channelized system. During the summer and fall months th canal is often stratified and dissolved oxygen concentrations range from about 2.0 mg per liter at the surface to < 1.0 mg per liter at depths below 1 m. By reducing light penetration, construction-generated turbidity could depress dissolved oxygen concentrations within the surface strata even further. There also may be a potential for construction to cause the canal to overturn and mix de-oxygenated water from the subsurface layer with the water of the oxygenated surface layer.

Another potential water quality issue involves effects of flow over the test fill plug and degraded spoil area, and the diversion of flow from the canal to adjacent remnant river channels. The test-fill location occurs downstream of a weir that has already diverted a portion of canal discharge (up to 60% during high flows) through the main remnant river channel. This diverted flow has flushed accumulated organic deposits out of the main adjacent remnant river channel without any detectable increases in nutrient loads downstream. However, because the test-fill plug will divert all canal flow through this remnant river channel, and another short section of remnant river immediately

upstream of the plug, there is a possibility that more deposits of organic matter and associated nutrients will be flushed downstream. At high flows, water will flow over the test-fill plug and degraded spoil area and nutrients from any newly exposed organic soils will be released.

The ecological evaluation studies for the test-fill project are designed to address four water quality hypotheses:

Hypothesis #1 - There will be no increase in downstream transport of suspended solids to S-65B resulting from placement of the plug as determined by comparison with the upstream control site.

Hypothesis #2 - Turbidity levels at sites in the vicinity of the test-fill plug (see sites below) will not be significantly different from the upstream control site within three months after completion of test-fill construction.

Hypothesis #3 - There will be no increase in nutrient concentrations or loads at S-65B as compared to the upstream control site.

Hypothesis #4 - Dissolved oxygen regimes (profiles) in the vicinity of the test-fill plug (see sites below) will not be significantly different from the upstream control site within three months after completion of test-fill construction.

These hypotheses will be evaluated by sampling at eight sites (Fig. 5):

Site 1 - Mid-canal location immediately upstream from the confluence of the remnant river channel adjacent to the lowermost Demonstration Project weir. This site will provide data on ambient water quality for the canal upstream of the test fill plug, and the source of inflow to the main remnant river channel adjacent to the plug.

Site 2 - Mid-remnant river channel location slightly north of the location of the test fill plug. This site will provide information on changes in water quality associated with flow through the remnant river channel.

Site 3 - Mid-canal location approximately 100 m downstream of the test fill plug. This site will provide information on localized effects of the test fill on water quality in the canal.

Site 4 - Mid-remnant river location at the confluence with the canal downstream of the test fill plug. This site will provide information on localized effects of the test fill, and any associated lateral diversion of flow, on water quality in the main remnant river channel adjacent to the test fill plug.

Site 5 - Mid-canal location immediately upstream of S-65B. This site will provide information on the downstream extent of any influence of the test fill on water quality, data for which are available from 1972 to the present.

During the permitting process three additional sites were added to the water quality monitoring plan:

Site 1a - Mid-canal location approximately 100 m downstream of Weir No. 1.

Site 1b - Mid-canal location approximately 300 m upstream of the test fill plug.

Site 6 - Mid-canal location approximately 500 m downstream of S-65B.

The historical database (1972 - present) of monthly water quality samples from the canal immediately upstream of S-65B will be analyzed to establish pre-construction baseline conditions and variability, and to optimize sampling frequencies for turbidity, suspended solids and nutrient parameters. Baseline conditions for dissolved oxygen regimes will be provided by one year of bi-weekly dissolved oxygen profiles at 1 m depth intervals from several canal and remnant river locations in the vicinity of the test-fill site. In addition, seven months of pre-construction data on these water quality parameters have been collected at the five test- fill sampling sites. These data will indicate the extent of any longitudinal variation.

The hypothesized "localized" (in the immediate area of the test fill) and "temporary" (several months) effects of the test-fill construction on water quality parameters will be tested by comparisons of data collected on each parameter at the three canal stations during three 3-month sampling intervals (pre-construction, during construction, and post-construction). Significant differences between the upper and lower stations (sites 1 and 5) during either the construction or post-construction sampling interval would indicate that the effects of construction were localized. Should this occur, the source of the downstream impacts will be identified more precisely through analyses of data collected at sites 2, 3 and 4. Further, significantly differences between the upper and lower stations during the post-construction sampling interval would indicate that the effects of construction were perpetuated. Subsequent sampling will indicate how long any downstream effects occur.

Suspended solids, turbidity, and nutrient fractions (orthophosphate, total dissolved phosphorus, total phosphorus, nitrate, nitrite, ammonia, total Kjeldahl nitrogen, and total dissolved Kjeldahl nitrogen) will be sampled at sites 1-5 using a Niskin-type sampling bottle at a depth of one meter. Grab samples have been collected at weekly intervals at sites 1-5 beginning in September 1993, and at sites 1a, 1b, and 6b beginning in March of 1994 and will continue for at least one year after construction is completed. More frequent (daily) samples will be collected periodically during construction and during high discharge periods. Periodic suspended solids samples also will be collected at depths of 4 m and 7 m at site 3 and site 5 during the construction period. An additional sampling site on the test-fill plug may be added to this sampling regimen after construction is complete.

Weekly Hydrolab measurements of dissolved oxygen concentrations have been taken along the surface to bottom depth profile at sites 1-5 beginning in September 1993 and at sites 1a, 1b, and 6 beginning in March of 1994 will continue for at least one year after construction is completed. Dissolved oxygen and temperature also will be sampled with continuous recorders set at depths of one meter at sites 1, 3 and 5 beginning at least one month prior to construction and continuing for one year after construction is completed.

During construction, surface, mid-depth, and bottom turbidity samples will be taken at all sites except site 2 twice daily. Quality control/quality assurance measures will be taken for all water quality sampling. Samples for suspended solids and nutrients will be preserved at 4°C and analyzed within 7 d and 28 d of collection respectively.

3.4.2 Test-Fill Evaluation Plan - Nature and Rate of Re-establishment of Wetland Plant Communities on the Backfilled Canal and Degraded Spoil Area.

Post-test-fill evaluation studies are designed to address a specific hypothesis: The wetland plant community re-established on the test fill plug and the spoil area brought down to grade will have a species composition comparable to that which existed on this section of floodplain prior to channelization.

This hypothesis will be evaluated from annual remote sensing information together with random quadrat sampling on the test fill site and the adjacent 5.2 ha area where the spoil bank will be brought to grade (Fig. 5). Plant species composition will be documented within 30 randomly placed 1 m^2 quadrats within both the test-fill and degraded spoil areas. Plant species composition will be documented within both areas after construction is completed and seasonally for four subsequent years. Ten 0.5 m^2 standing crop biomass samples will be taken at random points within the test-fill plug area and re-graded spoil areas in September-November 1994 (at the end of the peak growing season) and continuing for three subsequent years. Plant community information will be compared to previously collected plant community composition and standing crop biomass data from existing floodplain wetlands in the lower end of Pool B.

3.5 Modeling Upper Basin Hydrology and Reservoir Operation

The UKISS model will be used to evaluate alternative flood control and operation schedules for the upper Kissimmee chain of lakes in order to maintain wetland areas in the upper basin, provide flood protection, and deliver sufficient volume of water to the Kissimmee River to achieve the planned restoration. Both the timing and quantity of discharges to the Kissimmee River will be considered in the selection of a flood control and operation schedule. Alternative schedules will be chosen for evaluation based on consultations with the U. S. Army Corps of Engineers. Evaluations will continue to be conducted after implementation of the Headwaters Revitalization

Program as new information about the Kissimmee River system becomes available through data collection and analysis.

Prior to the evaluation of alternative flood control and operation schedules, the UKISS model will be redesigned and rewritten. In its present form, the model is difficult and inefficient to use. Also, UKISS can not execute in a predictive mode. The redesign would take advantage of the latest computer technologies to make model use easier and more efficient. One technology, object oriented programming, will also make UKISS extendible to the lower Kissimmee River basin. Once the redesign is complete, UKISS also will be capable of executing in a predictive mode, making the simulation of alternate conditions with hypothetical meteorological data possible.

A rewrite of UKISS would also provide additional benefits. Because it would be easier to use, the model could be executed by more people to address planning, regulation, and research. The ability to execute in forecast mode also would mean that UKISS could be used for real-time simulations to determine how best to operate flow control structures during storm events.

3.6 Post-construction Evaluation

This phase will be the most complex aspect and of longest duration. Restoration of some biological components could be a relatively slow process, but documentation of short-term trends will provide critical information for the fifth phase of the evaluation program, adaptive management.

SECTION IV

IMPLEMENTATION SCHEDULE

The schedule for the restoration evaluation program is dictated by planned construction milestones. Reference and baseline conditions for all evaluation components need to be established prior to initiation of the first phase of canal backfilling, which is scheduled to begin in 1998. Similarly, reference and baseline conditions for the headwaters project need to be established prior to the planned initiation of this component in 1995.

To most efficiently use staff and to meet budgetary commitments, the establishment of reference and baseline conditions for the first reach of backfilling will be phased over the five year period of the Research Plan. Reference conditions for all components will be defined by November 1994. Although some subsequent refinements may occur, the scope of each set of reference conditions must be largely established prior to design and implementation of the field studies component of the baseline evaluation phase. The design of baseline studies for fish and invertebrate communities, including any pilot studies that are needed to establish sampling methodology or protocol, will be completed by May 1995. The study designs for fish and invertebrates will be reviewed by the Scientific Advisory Panel (see RESOURCES) in July 1994, after which baseline studies of these components will be initiated. Study designs for compiling baseline data for other evaluation components will be completed in 1994, with initiation of these studies occurring in 1995.

The redesign of the UKISS model would begin in October 1994, and should last approximately eighteen months. The model would be used to determine an optimal flood control and operation schedule for lakes in the headwaters region on a continuing basis, as new information about the upper and lower basins becomes available during the main restoration.

Scheduled construction milestones and associated evaluation requirements form the basis for the pre-construction implementation timeline shown in the GANTT Charts (Fig. 4).

SECTION V

RESOURCES

The authorized project costs are based upon the 1991 U.S. Army Corps of Engineers feasibility report on the restoration project, which allocate $180,000 for upper basin monitoring and $15,642,000 for the lower basin hydrologic ecological evaluation program. The breakdown below shows approximate projected preliminary cost allocations for lower basin evaluation components for the pre-construction reference and baseline condition phases and 15 years of subsequent evaluation studies. GIS and modeling efforts will be associated with each of these categories and the cost will be part of the project areas or obtained from other sources

Avian Studies	$1.8 M
Fish Studies	$3.0 M
Habitat Structure and Stability	$1.7 M
Hydrologic Studies	$2.5 M
Invertebrate Studies	$2.5 M
Vegetation Studies	$2.3 M
Water Quality Studies	$1.7 M
Mobile Research Lab	$142 K

The first five years of the restoration evaluation program will be implemented primarily by the South Florida Water Management District with some collaborative work with the Florida Game and Fresh Water Fish Commission. Other participants could include the U.S. Army Corps of Engineers, U.S. Fish and Wildlife Service, Florida Department of Environmental Protection, experts from academia, and services of private consulting firms. Further definition of the participatory roles of the various state and federal agencies will be an early step in the implementation plan. An independent Scientific Advisory Committee has been commissioned to guide and review research and evaluation activities to provide independent expertise to judge the restoration evaluation program.

The redesign and rewrite of the UKISS model will be conducted primarily by the District in consultation with the U. S. Army Corps of Engineers. Other participants would be drawn from the District's expert assistance pool. Evaluations of alternative flood control and operation schedules would be conducted by both the District and the Corps.

As local sponsor of the restoration project, the District will assume the leadership role in the coordination and integration of the research efforts. The District also will have an active research team. Staffing of the District research team presently includes one Senior Environmental Scientist (Team Leader), one Staff Environmental Scientist, and one Senior Scientific Technician. A Distinguished Scientist position has been committed part time to the project and additional personnel requested in the 1995 budget.

Table 1. Kissimmee River Restoration Research Projects

Figure 1. Kissimmee River Restoration Research Expenditures and Milestones
Figure 2. Kissimmee River Restoration Goal, Objectives, Attributes and Information Needs
Figure 3. Research Questions
Figure 4. GANTT Chart
Figure 5. Test-Fill Water Quality and Vegetation Sampling Sites

Kissimmee River Research Plan

Table 1. Kissimmee River Restoration Research Projects

Ref. No.	Title	Start	End	Organization	Product
1	Water quality characteristics of Kissimmee River	1971	1973	USGS	Lamonds, 1975
2	Water quality characteristics and benthic invertebrates of Kissimmee Chain of Lakes	1973	1975	SFWMD	Milleson, 1975 (Tech Pub 75-2 DRE-55)
3	Hydrology and water quality of Lower Kissimmee Basin		1976	University of Florida, Huber et al.	Final report, 1976
4	Special project to prevent eutrophication of Lake Okeechobee	1973	1976	Florida Dept. of Administration (multi-agency)	Report, 1976
5	Nutrient loads and assimilation in Chandler Slough	1974	1976	SFWMD	Federico et al., 1978 (Tech Pub 78-2, DRE-84)
6	Water quality characteristics of Upper Kissimmee Basin	1981	1982	SFWMD	Jones et al., 1983 (Tech Memo DRE-167)
7	Water Quality characteristics of Lower Kissimmee Basin	1973	1978	SFWMD	Federico, 1982 (Tech Pub 82-3, DRE-154)
8	Nutrient assimilation potential of restored Kissimmee River marshes	1974	1975	Fla. Div. of State Planning Fla Coastal Engrs	Final Report, 1975
9	Evaluation of restoration measures	1976	1983	Kissimmee River Coordinating Council	McCaffrey, et al 1977
10	Nutrient assimilation in Boney Marsh	1975	1991	SFWMD	Davis, 1981 (Tech Pub 81-1,DRE 127)
11	First feasibility study on Kissimmee River restoration	1975	1985	U. S. Army Corps of Engineers	Report, 1985
12	Effects of alternative Kissimmee River restoration measures on water quality	1982	1985	Water and Air Research, Inc.	Final report 1985
13	Water quality of river tributaries and evaluation of measures to reduce nutrient loads	1978	1982	SFWMD	Goldstein, 1985, 1990 (Tech Pub 86-2, DRE-222, KRR Symp. Proc 1990)
14	Second feasibility study on Kissimmee River restoration	1991	1991	U. S. Army Corps of Engineers	Report, 1991
15	Kissimmee River/Lake Okeechobee monitoring	1971	1971	Fla. Game and Fresh Water Fish Commission	Ager, 1971
16	Ecological characteristics of channelized Kissimmee River system and evaluation of restoration measures	1972	1982	Fla. Game and Fresh Water Fish Commission	Perrin et al., 1982
17	Dissolved oxygen studies on Kissimmee River tributaries	1983	1984	Fla. Institute of Technology	Final report, 1984
18	Water quality and macroinvertebrate monitoring during Kissimmee demonstration project	1984	1989	Fla. Dept. of Environmental Regulation	Rutter et al., 1986, 1989
19	Pool B dissolved oxygen	1989	1989	SFWMD	Toth, unpub. data
20	Analysis of 1988 Kissimmee River fish kill	1988	1988	SFWMD, Fla. Game and Fresh Water Fish Commission	Toth, et al., (KRR Symp. Proc, 1990)
21	Pool B demonstration project monitoring	1984	on-going	Fla. Game and Fresh Water Fish Commission	Wullschleger et al., 1990; Fla. Game and Fresh Water Fish Commission, 1992
22	C-3205 - Dissolved oxygen modeling study $125,000	1992	1994	Howard Searcy, Consulting Engineers	Due Feb, 1994
23	Restoration plan evaluations and preliminary design	1986	1990	SFWMD	Loftin et al., 1990
24	Evaluation of fish and wildlife resources of historic Kissimmee River	1948	1957	Fla. Game and Fresh Water Fish Commission	Report, 1957

Table 1. Kissimmee River Restoration Research Projects- continued

Ref. No.	Title	Start	End	Organization	Product
25	Water quality modeling of C-38	1974	1975	Water Resources Engineers	Final report, 1975
26	Evaluation of fish and wildlife resources of the historic Kissimmee River	1955	1958	U.S. Fish and Wildlife Service	Report, 1959
27	Impacts of channelization and evaluation of potential ecological benefits of water level manipulations	1972	1974	SFWMD	Dineen, et al, 1974 (in depth report, Vol 2, No. 2)
28	Effects of water level manipulations and other management measures on floodplain vegetation	1972	1973	SFWMD	Goodrick and Milleson, 1974 (Tech Pub 74-02, DRE-40)
29	Pre- and Post-channelization floodplain vegetation maps and cattle carrying capacity	1974	1976	Florida Div. of State Planning	Pruitt and Gatewood, 1976
30	Impacts of channelization on ecological resources	1979	1979	U.S. Fish and Wildlife Service Report	Report, 1979
31	Post-channelization floodplain vegetation communities	1978	1980	SFWMD	Milleson et al., 1980 (Tech Pub 80-07, DRE 113)
32	Impacts of channelization on Bald eagle nesting	1959	1979	Fla. Game and Fresh Water Fish Commission	Shapiro et al., 1982
33	Post-channelization Paradise Run fisheries	1987	1987	Fla. Game and Fresh Water Fish Commission	Davis, et al., 1990 (KRR Symp Proc, 1990)
34	Ecological impacts of channelization	1988	1988	SFWMD	Toth, 1990 (KRR Symp Proc, 1990)
35	Historical Kissimmee River fisheries	1955	1957	Fla. Game and Fresh Water Fish Commission & U. S. Fish and Wildlife Service	Miller, 1990 (KRR Symp Proc, 1990)
36	Impacts of channelization on fish and wildlife resources	1979	1979	Fla. Game and Fresh Water Fish Commission	Montalbano et al., 1979 (U.S.D.A. General Tech Report RM-65
37	Environmental benefits of water level manipulations in C-38 impoundments	1971	1973	SFWMD	Milleson, 1976 (Tech Pub 76-03, DRE-70)
38	Kissimmee River restoration recommendations	1988	1988	Fla. Game and Fresh Water Fish Commission	Egbert, 1990 (KRR Symp Proc, 1990)
39	Evaluation of measures to restore Kissimmee River waterfowl habitat	1988	1988	Fla. Game and Fresh Water Fish Commission	Johnson and Turnbull, 1990 (KRR Symp Proc, 1990)
40	Kissimmee River restoration recommendations	1988	1988	Karr	1990 (KRR Symp Proc, 1990)
41	Effects of reestablished flow and water level manipulations on littoral and floodplain vegetation	1984	1988	Fla. Game and Fresh Water Fish Commission	Miller et al., 1990 (KRR Symp Proc, 1990)
42	Effects of Pool B Demonstration Project on wading birds and waterfowl	1987	1988	Fla. Game and Fresh Water Fish Commission	Toland, 1990 (Krr Symp Proc, 1990
43	Required components of a Kissimmee River restoration plan	1988	1988	SFWMD	Toth, 1990 (KRR Symp Proc 1990)
44	Importance of flow to Kissimmee River fish communities	1088	1988	Fla. Game and Fresh Water Fish Commission	Wullshleger et al., 1990 (KRR Symp Proc, 1990)
45	Environmental responses to Kissimmee River demonstration project	1984	1988	SFWMD	Toth, 1991 (Tech Pub 91-02)
46	C91-2562-68 - $16,095 - Recommendations for ecological evaluation program for Kissimmee River restoration	1988	1988	Karr et al	Final Report, 1988

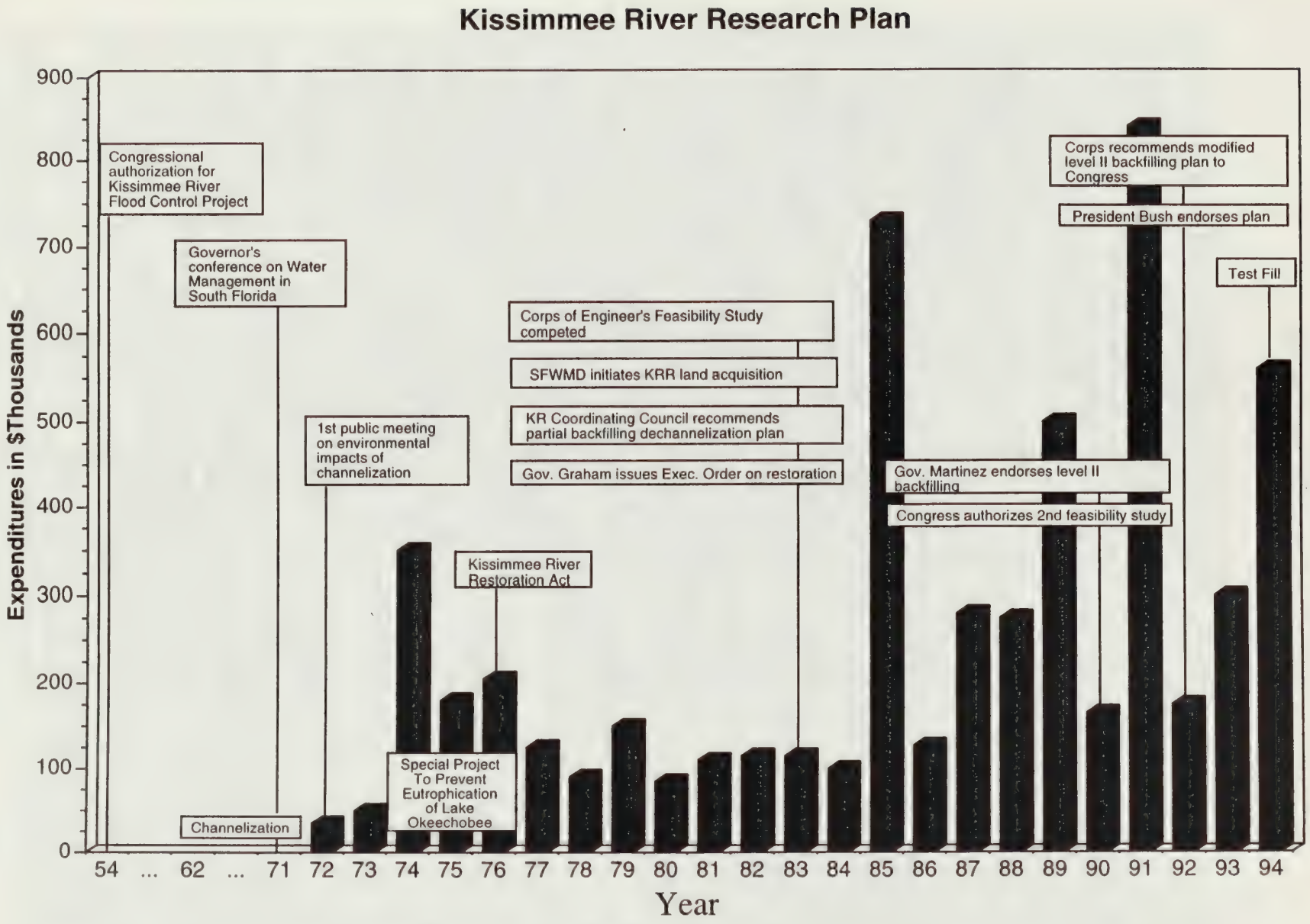

Kissimmee River Research Plan
Expenditures in $Thousands
900
800
700
600
500
400
300
200
100
0
Congressional authorization for Kissimmee River Flood Control Project
Governor's conference on Water Management in South Florida
1st public meeting on environmental impacts of channelization
Corps of Engineer's Feasibility Study competed
SFWMD initiates KRR land acquisition
KR Coordinating Council recommends partial backfilling dechannelization plan
Gov. Graham issues Exec. Order on restoration
Kissimmee River Restoration Act
Special Project To Prevent Eutrophication of Lake Okeechobee
Channelization
Gov. Martinez endorses level II backfilling
Congress authorizes 2nd feasibility study
Corps recommends modified level II backfilling plan to Congress
President Bush endorses plan
Test Fill
54 ... 62 ... 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94
Year

Figure 1. Kissimmee River Restoration Research Expenditures and Milestones

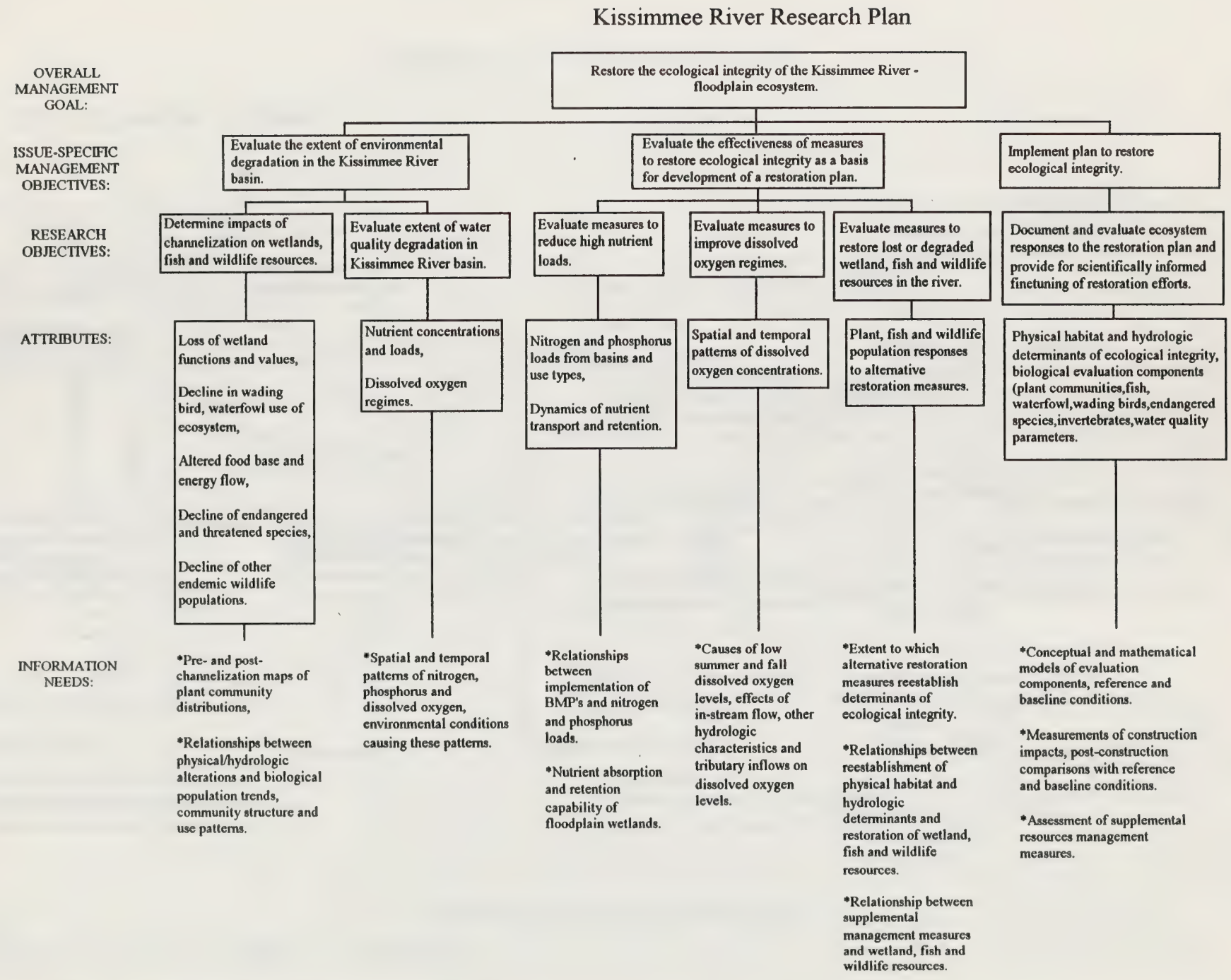

Kissimmee River Research Plan
OVERALL MANAGEMENT GOAL:
Restore the ecological integrity of the Kissimmee River - floodplain ecosystem.
ISSUE-SPECIFIC MANAGEMENT OBJECTIVES:
Evaluate the extent of environmental degradation in the Kissimmee River basin.
Evaluate the effectiveness of measures to restore ecological integrity as a basis for development of a restoration plan.
Implement plan to restore ecological integrity.
RESEARCH OBJECTIVES:
Determine impacts of channelization on wetlands, fish and wildlife resources.
Evaluate extent of water quality degradation in Kissimmee River basin.
Evaluate measures to reduce high nutrient loads.
Evaluate measures to improve dissolved oxygen regimes.
Evaluate measures to restore lost or degraded wetland, fish and wildlife resources in the river.
Document and evaluate ecosystem responses to the restoration plan and provide for scientifically informed finetuning of restoration efforts.
ATTRIBUTES:
Loss of wetland functions and values,
Decline in wading bird, waterfowl use of ecosystem,
Altered food base and energy flow,
Decline of endangered and threatened species,
Decline of other endemic wildlife populations.
Nutrient concentrations and loads,
Dissolved oxygen regimes.
Nitrogen and phosphorus loads from basins and use types,
Dynamics of nutrient transport and retention.
Spatial and temporal patterns of dissolved oxygen concentrations.
Plant, fish and wildlife population responses to alternative restoration measures.
Physical habitat and hydrologic determinants of ecological integrity, biological evaluation components (plant communities,fish, waterfowl,wading birds,endangered species,invertebrates,water quality parameters.
INFORMATION NEEDS:
*Pre- and post-channelization maps of plant community distributions,
*Relationships between physical/hydrologic alterations and biological population trends, community structure and use patterns.
*Spatial and temporal patterns of nitrogen, phosphorus and dissolved oxygen, environmental conditions causing these patterns.
*Relationships between implementation of BMP's and nitrogen and phosphorus loads.
*Nutrient absorption and retention capability of floodplain wetlands.
*Causes of low summer and fall dissolved oxygen levels, effects of in-stream flow, other hydrologic characteristics and tributary inflows on dissolved oxygen levels.
*Extent to which alternative restoration measures reestablish determinants of ecological integrity.
*Relationships between reestablishment of physical habitat and hydrologic determinants and restoration of wetland, fish and wildlife resources.
*Relationship between supplemental management measures and wetland, fish and wildlife resources.
*Conceptual and mathematical models of evaluation components, reference and baseline conditions.
*Measurements of construction impacts, post-construction comparisons with reference and baseline conditions.
*Assessment of supplemental resources management measures.

Figure 2. Kissimmee River Restoration Goal, Objectives, Attributes, and Information Needs.

KISSIMMEE RIVER RESEARCH PLAN

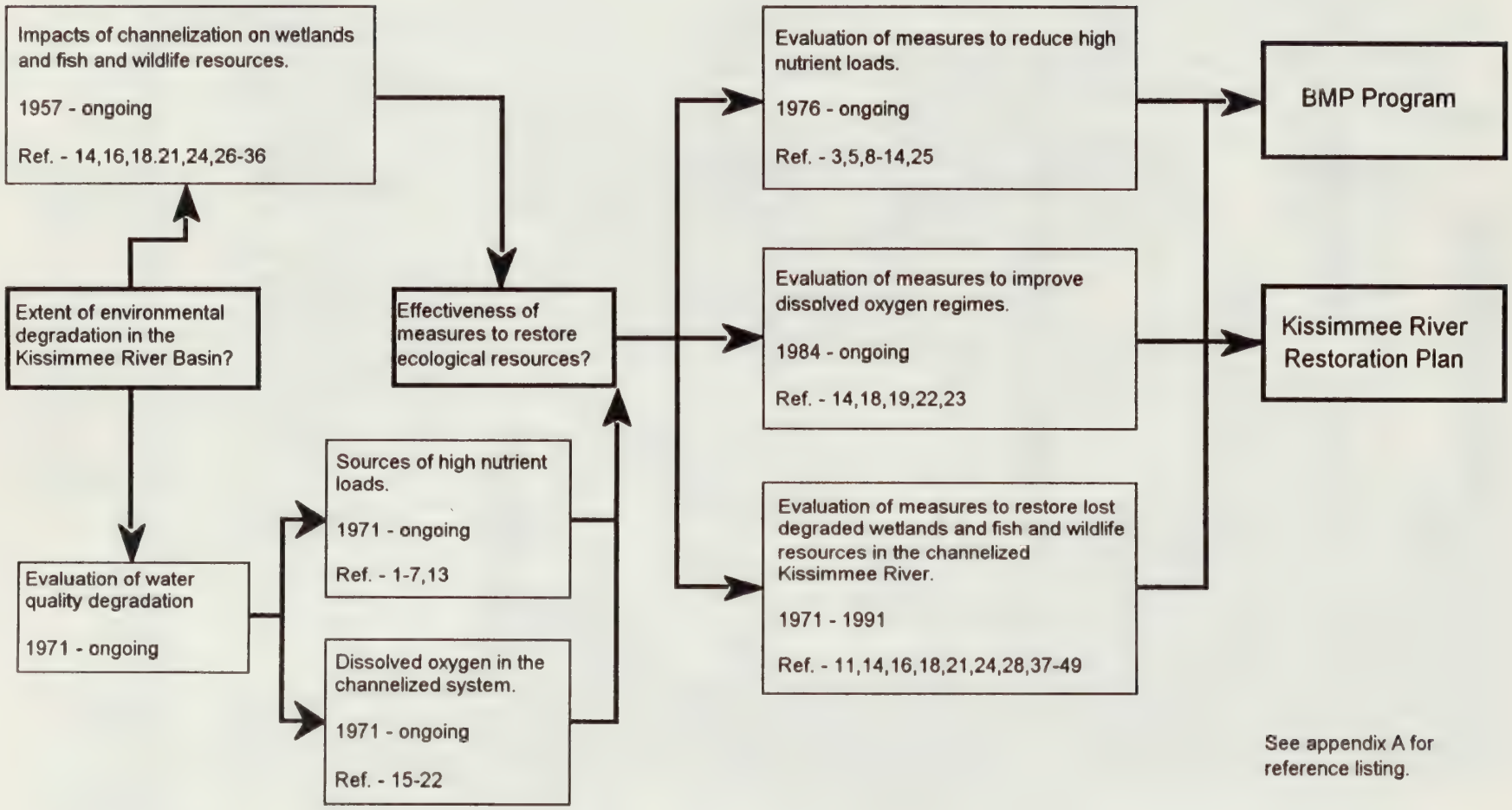

Impacts of channelization on wetlands and fish and wildlife resources.
1957 - ongoing
Ref. - 14,16,18.21,24,26-36
Extent of environmental degradation in the Kissimmee River Basin?
Effectiveness of measures to restore ecological resources?
Evaluation of water quality degradation
1971 - ongoing
Sources of high nutrient loads.
1971 - ongoing
Ref. - 1-7,13
Dissolved oxygen in the channelized system.
1971 - ongoing
Ref. - 15-22
Evaluation of measures to reduce high nutrient loads.
1976 - ongoing
Ref. - 3,5,8-14,25
Evaluation of measures to improve dissolved oxygen regimes.
1984 - ongoing
Ref. - 14,18,19,22,23
Evaluation of measures to restore lost degraded wetlands and fish and wildlife resources in the channelized Kissimmee River.
1971 - 1991
Ref. - 11,14,16,18,21,24,28,37-49
BMP Program
Kissimmee River Restoration Plan
See appendix A for reference listing.

Figure 3. Research Questions

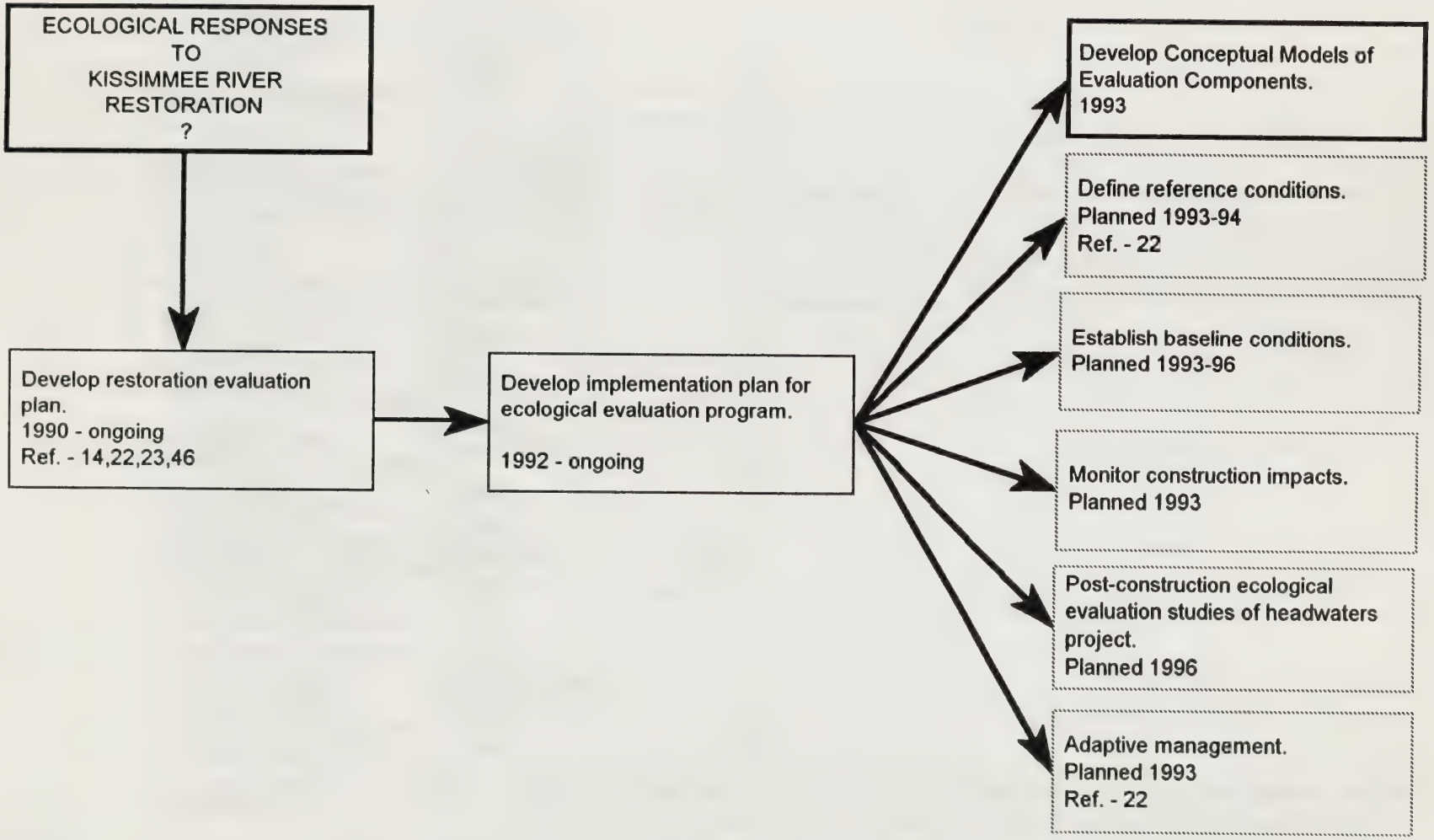


Figure 3. Research Questions (continued)

Kissimmee River Research Plan

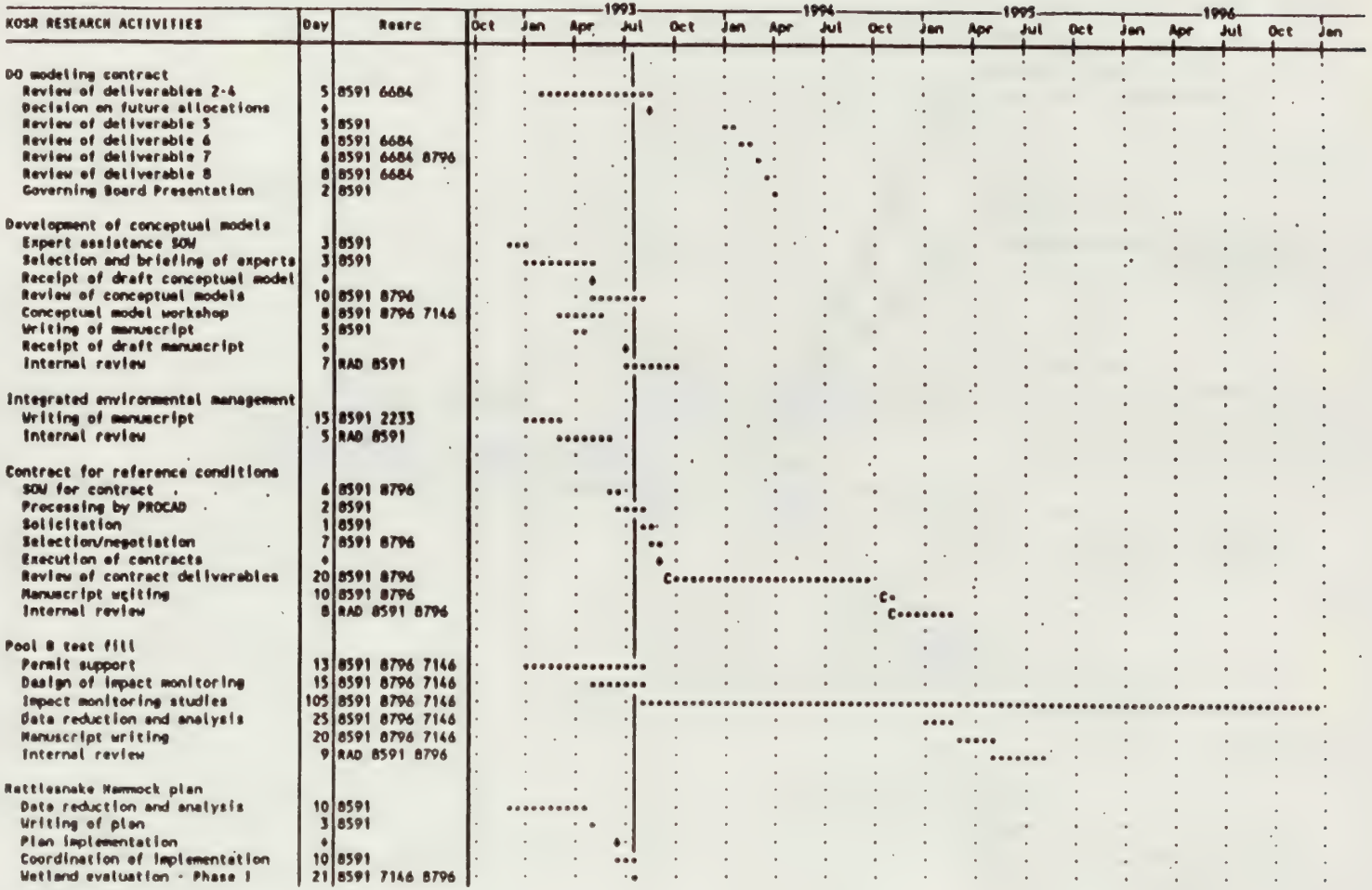

KOSR RESEARCH ACTIVITIES
Day
Resrc
1993
1994
1995
1996
Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan
DO modeling contract
Review of deliverables 2-4 5 8591 6684
Decision on future allocations
Review of deliverable 5 5 8591
Review of deliverable 6 8 8591 6684
Review of deliverable 7 6 8591 6684 8796
Review of deliverable 8 8 8591 6684
Governing Board Presentation 2 8591
Development of conceptual models
Expert assistance SOW 3 8591
Selection and briefing of experts 3 8591
Receipt of draft conceptual model
Review of conceptual models 10 8591 8796
Conceptual model workshop 8 8591 8796 7146
Writing of manuscript 5 8591
Receipt of draft manuscript
Internal review 7 RAD 8591
Integrated environmental management
Writing of manuscript 15 8591 2233
Internal review 5 RAD 8591
Contract for reference conditions
SOW for contract 6 8591 8796
Processing by PROCAD 2 8591
Solicitation 1 8591
Selection/negotiation 7 8591 8796
Execution of contracts
Review of contract deliverables 20 8591 8796
Manuscript writing 10 8591 8796
Internal review 8 RAD 8591 8796
Pool B test fill
Permit support 13 8591 8796 7146
Design of impact monitoring 15 8591 8796 7146
Impact monitoring studies 105 8591 8796 7146
Data reduction and analysis 25 8591 8796 7146
Manuscript writing 20 8591 8796 7146
Internal review 9 RAD 8591 8796
Rattlesnake Hammock plan
Data reduction and analysis 10 8591
Writing of plan 3 8591
Plan implementation
Coordination of implementation 10 8591
Wetland evaluation - Phase I 21 8591 7146 8796

Figure 4. Gantt Chart. Time lines for KOSR Kissimmee River Research program tasks/activities. Days adjacent to activities are total number of days estimated for all staff combined to complete activity. Resource summary utilization chart (page 16).

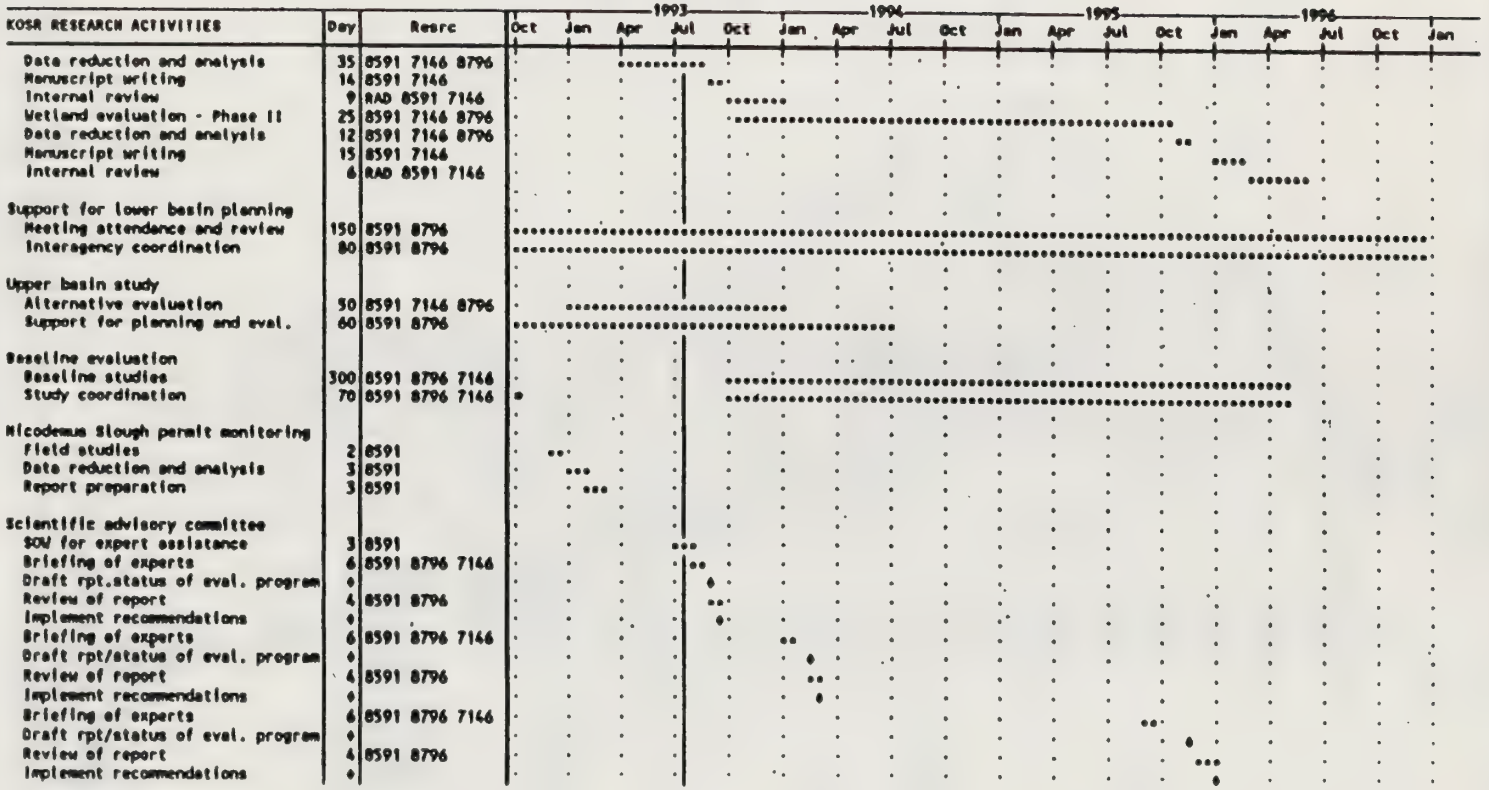

KOSR RESEARCH ACTIVITIES
Dur
Resrc
1993
1994
1995
1996
Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan Apr Jul Oct Jan
Data reduction and analysis 35 8591 7146 8796
Manuscript writing 14 8591 7146
Internal review 9 RAD 8591 7146
Wetland evaluation - Phase II 25 8591 7146 8796
Data reduction and analysis 12 8591 7146 8796
Manuscript writing 15 8591 7146
Internal review 6 RAD 8591 7146
Support for lower basin planning
Meeting attendance and review 150 8591 8796
Interagency coordination 80 8591 8796
Upper basin study
Alternative evaluation 50 8591 7146 8796
Support for planning and eval. 60 8591 8796
Baseline evaluation
Baseline studies 300 8591 8796 7146
Study coordination 70 8591 8796 7146
Nicodemus Slough permit monitoring
Field studies 2 8591
Data reduction and analysis 3 8591
Report preparation 3 8591
Scientific advisory committee
SOW for expert assistance 3 8591
Briefing of experts 6 8591 8796 7146
Draft rpt.status of eval. program
Review of report 4 8591 8796
Implement recommendations
Briefing of experts 6 8591 8796 7146
Draft rpt/status of eval. program
Review of report 4 8591 8796
Implement recommendations
Briefing of experts 6 8591 8796 7146
Draft rpt/status of eval. program
Review of report 4 8591 8796
Implement recommendations

Figure 4 Continued Resource summary utilization chart provides KOSRD staff names associated with employee numbers, the number of days they are available for KOSRD program assignments per quarter, and the actual number of days per quarter an employee is currently assigned to Research activity. See legend for identification symbols.

Kissimmee River Research Plan

KOSR RESEARCH ACTIVITIES	Dur	Resrc	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan
			1993					1994				1995				1996				
Resource summary																				
Utilization																				
KATHLEEN KAUWERT	48.9	7006																		
ROBERT CHAMBERLAIN	48.9	4574																		
NETTIE WINOGRAD	48.9	4112																		
KAREN LYTNOE	48.9	7820																		
MARK BRADY	48.9	0417																		
NICK ALMEN	45.6	2233			3.0															
TOM JAMES	48.9	5791																		
BRADLEY JONES	32.6	2351																		
DERA MUSZICK	48.9	5114																		
ERIC FLAIG	48.9	6263																		
TODD TISDALE	45.6	6684			2.0				8.0											
JOYCE ZHANG	48.9	1075																		
CHARLES HANLON	48.9	2411																		
BARBARA BROWN	48.9	6864																		
ALBREY ARRINGTON	45.6	7146			10.4	22.6	28.3	30.9	30.6	19.5	19.2	18.3	25.8	8.6	8.5	11.5	10.5	2.3		
RESEARCH APPRAISAL DIVISION	65.2	RAD			0.7	1.3	1.9	2.1	0.0			1.0	1.1	1.4	0.7		0.6	1.4		
LOU TOTH	45.6	8591	25.2	64.8	60.2	72.9	57.5	59.9	36.9	27.3	30.9	23.1	17.1	13.9	10.5	13.5	2.3			
JOE KOEBEL	45.6	8796	18.6	28.7	41.2	47.6	53.7	56.3	37.3	32.0	37.0	35.2	21.7	14.4	13.5	6.5	2.3			
KARL HAVENS	45.6	5859																		
ROB SOSNOVSKI	45.6	3749																		
Total days			43.8	109.6	125.3	150.7	144.2	154.8	93.7	78.5	87.2	85.2	48.8	37.5	35.5	39.1	8.3			

Legend

▪▪▪▪▪	Activity	♦	Milestone
C▪▪▪▪	Activity on critical path	L▪▪▪▪	Locked activity
═▪▪▪▪	Partially completed activity	═══	Completed activity
▲	Original start date	▼	Original end date
.....	Discontinuous activity	.....♦	Baselined milestone

Figure 4 Continued

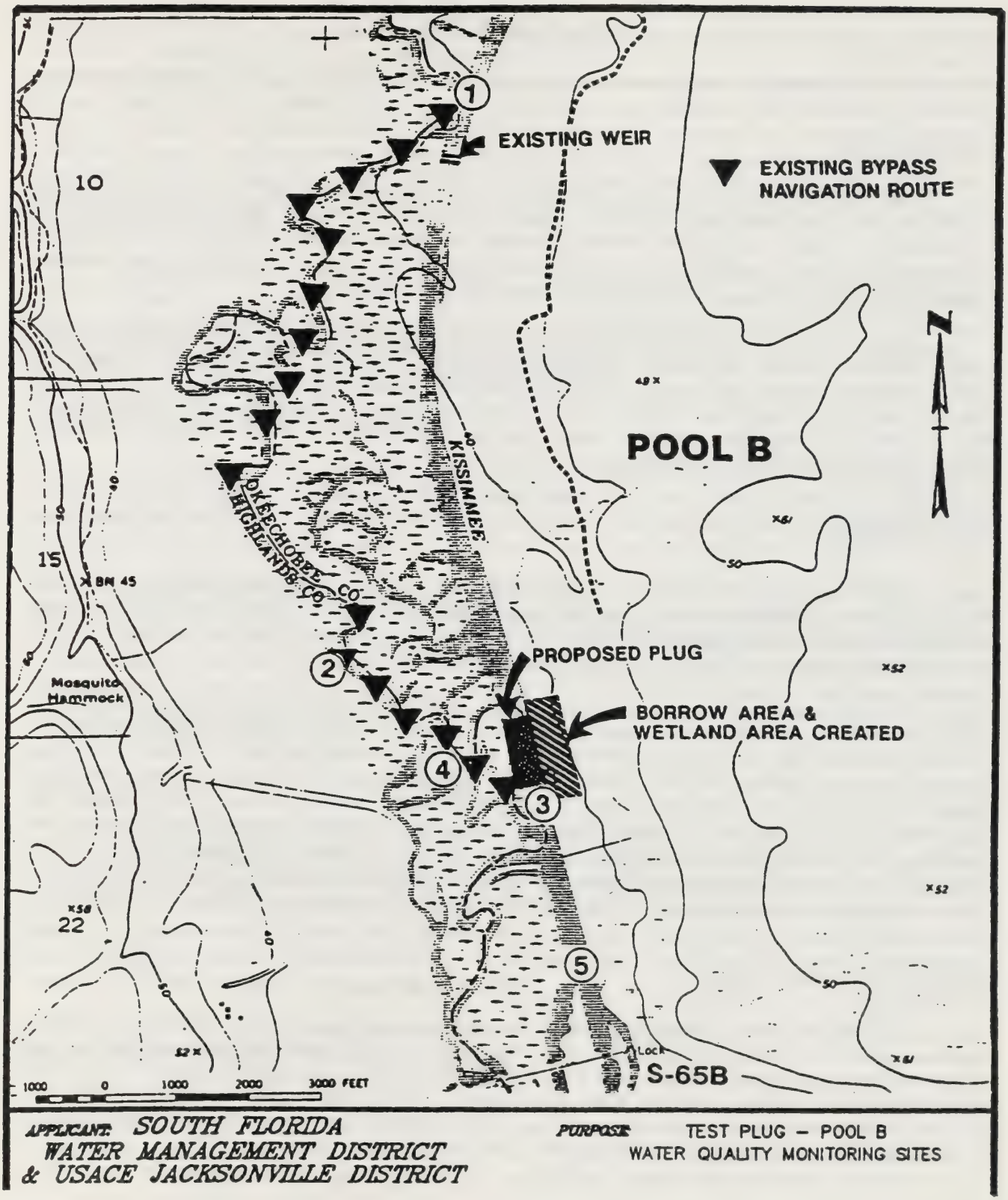


Figure 5. Test-Fill Water Quality and Vegetation Sampling Sites

SUBREGION 2:

LAKE OKEECHOBEE

BACKGROUND

Lake Okeechobee, covering over 1732 km^2 (669 mi^2), is the "liquid heart" of the once contiguous Kissimmee/Lake Okeechobee/Everglades system (Figure 1). The lake has an average depth of approximately 2.7 m (9 ft) and occurs as a broad, shallow, bedrock depression. The lake provides flood protection by functioning as a storage basin, serves as a primary source of water for consumptive uses in South Florida, supports a valuable commercial and sport fishery, and provides critical habitat for fish and wildlife.

Inflows enter Lake Okeechobee from the Kissimmee River basin, Taylor Creek, Nubbin Slough, Fisheating Creek, Nicodemus Slough, and the Lake Istokpoga basin (Indian Prairie Canal and Harney Pond Canal), and contiguous areas. Some drainage from the EAA is also periodically backpumped into the lake. The lake's largest outlets include the St. Lucie Canal eastward to the Atlantic Ocean and the Caloosahatchee Canal and River to the Gulf of Mexico. The four major agricultural canals (West Palm Beach, Hillsboro, North New River, and Miami) drain to the south into the Everglades region.

MAJOR ISSUES

Physical, chemical, and biological attributes of the lake and its tributaries and distributaries have been significantly altered since construction of the Central and Southern Florida Flood Control Project. The alterations have been brought about by changes in hydrology (timing, direction, route of flow, lake stage), increased nutrient and contaminant inputs, an introduction of exotic species of flora and fauna.

Prior to drainage, lake stage was controlled by rainfall and evapotranspiration; water quality was determined by basin geology; a large, dynamic, and heterogeneous littoral zone existed along the northwestern shore; and surface water outflows were southward via sheetflow to the northern Everglades. Currently, lake stage follows a regulation schedule designed to maximize storage capacity prior to the wet season and water availability during the dry season. The lake is considered to be highly eutrophic as a result of increased nutrient loading from agricultural and urban land in the drainage basin and backpumping of waters from the EAA. The extent and dynamics of the littoral zone are confined by the Herbert Hoover Dike. Large areas are dominated by cattails (*Typha latifolia, T. domingensis)*, torpedo grass (*Panicum repens*), hydrilla (*Hydrilla verticillata*), or melaleuca (*Melaleuca quinquenervia*). Surface outflows are via channelized connections to the estuaries and southeastern wellfields.

PREVIOUS SCIENCE PLANS

A series of science and management plans have been developed for the lake in response to increasing concerns about water quality and supply. Four plans were reviewed prior to developing the restoration goals and science strategies outlined in this chapter: Lake Okeechobee Technical Advisory Committee report (LOTAC-I 1986), Lake Okeechobee Technical Advisory Council final report (LOTAC-II 1990), Lake Okeechobee SWIM Plan (SFWMD 1993b), and Lake Okeechobee Research Plan (SFWMD 1993a). An overview of science activities specific to water quality and environmental resources in each of the four documents follows.

Lake Okeechobee Technical Advisory Committee

In August 1985, the Governor requested the Secretary of the FDER take the lead in conducting a study of conditions that affect water conservation and quality and biological characteristics of Lake Okeechobee. In response, the Secretary established LOTAC-I. This committee reported phosphorus levels doubled in the lake over the period 1973-1984, the lake was losing its ability to assimilate phosphorus, and water demands stress available supply during periods of drought (LOTAC 1986). A list of management alternatives to reduce phosphorus loading by 40% and increase water supply were provided. LOTAC-I did not consider the potential impacts of nutrient diversion proposals upon other potential receiving systems. The committee recommended development and implementation of a coordinated monitoring and research plan with focus on phosphorus sources and dynamics, best management practices, downstream impacts of proposed diversions, effects of lake levels on biological communities, and comprehensive fish surveys.

Partially in response to this recommendation, the SFWMD initiated the Lake Okeechobee Ecosystem Study to assess the lake ecosystem status and trends, gain greater understanding of the causes of nuisance algal blooms, and assess ecosystem impacts of various lake levels. The results of this study were recently published in a dedicated issue of *Archiv für Hydrobiologie* (Aumen and Wetzel 1995). This publication is cited as a single document in the bibliography to this chapter; the 20 papers are not listed individually.

Lake Okeechobee Technical Advisory Council

LOTAC-II was created by the Florida Legislature through the Surface Water Improvement and Management Act of 1987 and was continued by Executive Order through March 1990. The final goal of the LOTAC-II was to make findings and recommendations for permanently eliminating adverse environmental effects of past and proposed diversions of nutrient-rich water from the lake.

Preliminary results of research projects undertaken in response to recommendations in the LOTAC-I report (LOTAC-I 1986) were presented to LOTAC-II and were used in making recommendations. The findings and recommendations for Lake Okeechobee focused on the draft interim SWIM plan (SFWMD 1989) and included completion and implementation of the SWIM Plan and continuation of ongoing research efforts undertaken to address issues outlined in the 1986 LOTAC-1 report. In particular, LOTAC-II stressed the need for interpreting monitoring data (water quality) to determine relationships between climatological and hydrological events and resultant runoff of phosphorus.

Surface Water Improvement and Management Plan

The SWIM Act adopted by the Florida legislature in 1987 required the SFWMD to: 1) implement the LOTAC-I recommendations except those that might have adverse impact elsewhere and 2) develop a SWIM plan for Lake Okeechobee to address point and nonpoint source pollution, destruction of natural systems, correction and prevention of surface water problems, and research for better management of surface waters and associated natural systems. The Lake Okeechobee SWIM Plan (SFWMD 1993b) contains a series of goals, objectives, and strategies in seven categories (water quality, environmental resources, water supply, flood protection, recreation, navigation, and public information). Specific science strategies include:

- Determine the extent to which Class I and Class III water quality standards are exceeded in the lake and within all inflows and upstream tributaries to the lake.

- Determine the phosphorus uptake capacity of lake sediments and identify key processes affecting its ability to assimilate and retain phosphorus.

- Perform an assessment of current water quality trends within the lake and at all tributary inflows.

- Update the Lake Okeechobee nutrient budget to reflect in-lake and tributary phosphorus loading trends and identify basins out of compliance with the phosphorus performance standard.

- Identify and quantify nitrogen cycling, sources and sinks within the Lake Okeechobee watershed.

- Develop appropriate nitrogen loading and concentration criteria for nitrogen inputs into the lake if necessary and appropriate.

- Develop and maintain a quantitative database to monitor long-term changes in the lake's biological communities (i.e., phytoplankton, invertebrate, fish, macrophytic, and avian) in response to changing water quality and hydrological conditions.

- Develop and implement management programs to enhance the native vegetation communities of the Lake Okeechobee littoral zone.

Lake Okeechobee Research Plan

The LORP (SFWMD 1993a) defines a series of research objectives and information needs to support the goal to protect and improve the water quality and ecosystem health of Lake Okeechobee. The plan addresses seven research objectives:

- Determine ecosystem status and trends. Measurement and documentation of the lake's current status, across its wide range of ecological attributes, will provide a foundation for long-term assessment of potential changes and selection of management strategies.

- Determine causes of algal blooms. The spatial and temporal extent of algal blooms, common during summer months, must be documented in order to address management options designed to reduce the blooms. Factors controlling blooms must be identified, especially their relationship to nutrient inputs.

- Determine water quality trends. Declining water quality has been the major focus of science efforts in Lake Okeechobee since the late 1960s. Nutrient concentrations in lake water and sediments are important to the entire biological system. Phosphorus has been identified as the most important parameter relative to declining ecosystem health; input from agricultural activities north of the lake is the largest source of phosphorus. Long-term water quality data are needed, along with information on the relationship between water quality and hydrologic conditions.

- Determine effectiveness of measures to improve water quality. Declining water quality has led to regulations designed to reduce inflow of nutrients, particularly phosphorus, the parameter most likely to respond to alterations in land management. Research and demonstration projects on BMPs have been implemented to reduce nutrient input and improve water quality. Evaluation of these should include relationships between BMPs, phosphorus loading, and ecosystem attributes; movement of water and nutrients between the open lake and littoral zone; and relationships between phosphorus loading and rainfall.

- Determine sources and fates of critical elements. Thorough understanding of nutrient dynamics, in both the lake itself and the entire basin, is needed for analysis of water quality trends and BMP effectiveness. It important to know the potential long-term contribution of stored sediment phosphorus to water column phosphorus and its relationship to phosphorus loading.

- Determine effects of lake levels. Regulation of water level is one of the most viable management options for improving ecosystem health, while still maintaining adequate water supply during droughts and flood protection. Water level can affect many biological communities, including littoral zone vegetation, wading bird populations, algal blooms, the Everglades through changing water supply, and estuaries through changing discharges.

- Measure parameters related to numerical water quality standards. Lake Okeechobee is utilized as a source of drinking water and for human-contact recreation, and its waters must comply with Class I and III standards. It is necessary to know concentrations of applicable standards at inflows and relationships between the standards and point and nonpoint pollutant sources.

INFORMATION NEEDS

Restoration of Lake Okeechobee is dependent upon re-establishment of water quality, lake levels, and a littoral zone that will support a self-sustaining ecosystem. The key question is: Can hydrologic linkages between the Kissimmee River, Lake Okeechobee, and the Everglades be restored to a degree necessary to support a self-sustaining ecosystem similar to the historic system, while providing flood protection, water supply, and a sustainable economic system?

The Science Subgroup previously developed a series of ecological and hydrological restoration objectives for Lake Okeechobee (SSG 1993). For each objective, information needs were identified and approaches designed to meet those information needs. The results of this process are summarized in Figure 10 and outlined below. Under each critical science question is information on the approach and tasks recommended to answer the question.

Hydrological Restoration

Objectives

- Implement a more flexible regulation schedule that mimics historic natural hydrologic variability and enhances the expanded littoral zone ecosystem.

- Reestablish sheetflow for all (maximum) or all regulatory (minimum) discharges from the southern portion of Lake Okeechobee to convey historic flows to the central and southern Everglades.

Critical questions and approaches.

1. What is the system-wide water budget on a yearly basis since levee construction?

The first step toward allocation and management of water on a system-wide scale is to develop an accurate water budget. This will allow storage for flood control, needs of consumptive users, and requirements for a sustainable ecological system to be assessed on a system-wide basis.

- Acquire the necessary data to develop a system-wide water budget.

2. What dynamic regulation schedule will better mimic natural hydrologic variability?

A natural-system-type hydrologic model, incorporating the expanded littoral zone, should be used to investigate water-level fluctuation over a range of environmental conditions. Once this model is developed, it should be tested against the water budget data collected as to its accuracy. This will then allow amendments to be made, so that better predictive scenarios may be evaluated.

- Develop a "base" hydrologic model of lake stage that is coupled with inputs from the Kissimmee basin and rainfall.

- Use the "base" model to investigate changes in lake stage associated with various restoration alternatives, including but not limited to: reduced east-west discharges, changes in agricultural/urban water demands, interbasin transfer of water from the Caloosahatchee urban areas into the lake, and changes in levee configuration.

3. What are the potential impacts to the levee (structure, integrity, leakage) as a result of changes in regulation schedule?

- Perform engineering studies as required.

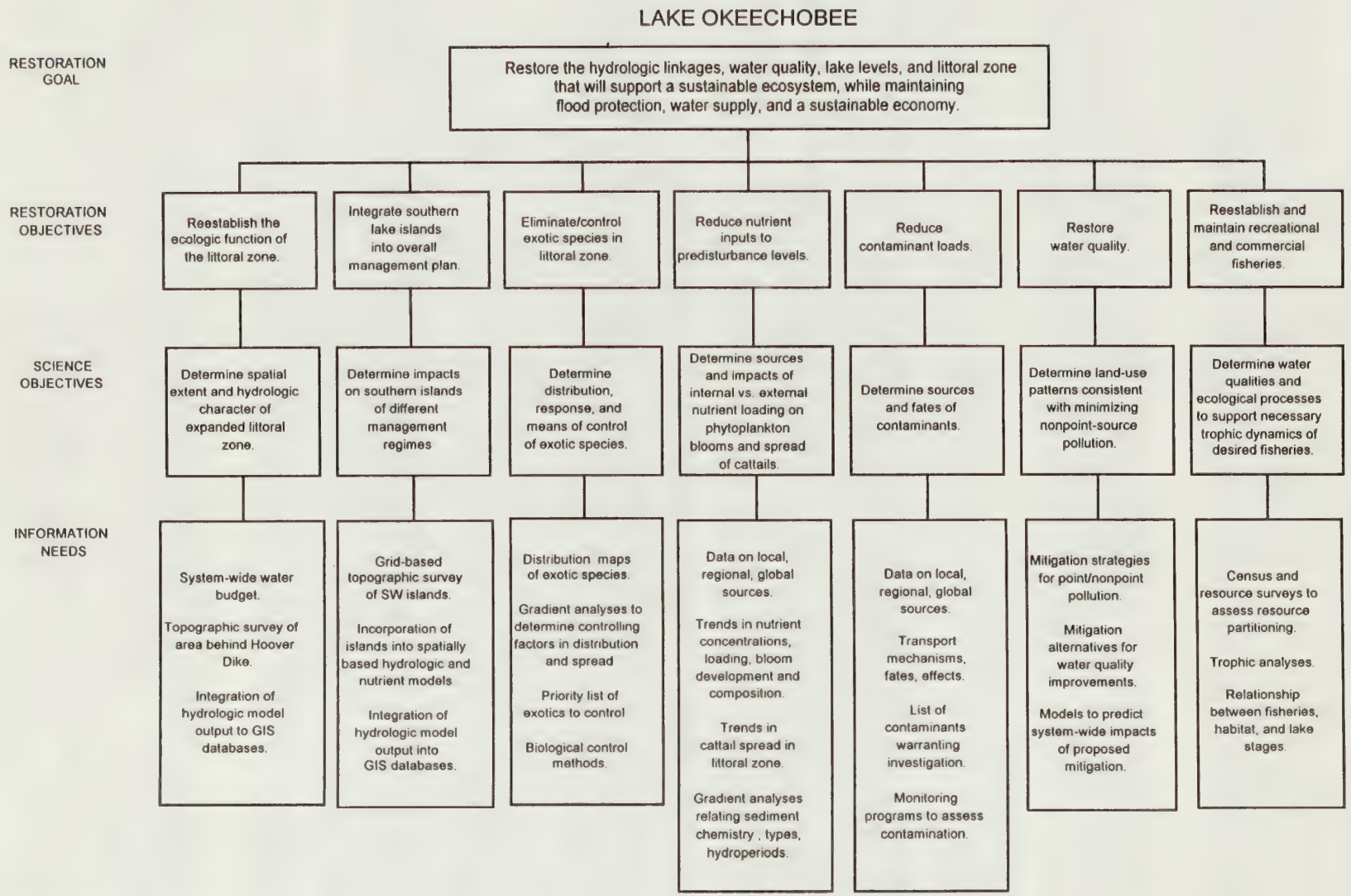

LAKE OKEECHOBEE
RESTORATION GOAL
Restore the hydrologic linkages, water quality, lake levels, and littoral zone that will support a sustainable ecosystem, while maintaining flood protection, water supply, and a sustainable economy.
RESTORATION OBJECTIVES
Reestablish the ecologic function of the littoral zone.
Integrate southern lake islands into overall management plan.
Eliminate/control exotic species in littoral zone.
Reduce nutrient inputs to predisturbance levels.
Reduce contaminant loads.
Restore water quality.
Reestablish and maintain recreational and commercial fisheries.
SCIENCE OBJECTIVES
Determine spatial extent and hydrologic character of expanded littoral zone.
Determine impacts on southern islands of different management regimes
Determine distribution, response, and means of control of exotic species.
Determine sources and impacts of internal vs. external nutrient loading on phytoplankton blooms and spread of cattails.
Determine sources and fates of contaminants.
Determine land-use patterns consistent with minimizing nonpoint-source pollution.
Determine water qualities and ecological processes to support necessary trophic dynamics of desired fisheries.
INFORMATION NEEDS
System-wide water budget.
Topographic survey of area behind Hoover Dike.
Integration of hydrologic model output to GIS databases.
Grid-based topographic survey of SW islands.
Incorporation of islands into spatially based hydrologic and nutrient models
Integration of hydrologic model output into GIS databases.
Distribution maps of exotic species.
Gradient analyses to determine controlling factors in distribution and spread
Priority list of exotics to control
Biological control methods.
Data on local, regional, global sources.
Trends in nutrient concentrations, loading, bloom development and composition.
Trends in cattail spread in littoral zone.
Gradient analyses relating sediment chemistry , types, hydroperiods.
Data on local, regional, global sources.
Transport mechanisms, fates, effects.
List of contaminants warranting investigation.
Monitoring programs to assess contamination.
Mitigation strategies for point/nonpoint pollution.
Mitigation alternatives for water quality improvements.
Models to predict system-wide impacts of proposed mitigation.
Census and resource surveys to assess resource partitioning.
Trophic analyses.
Relationship between fisheries, habitat, and lake stages.

Figure 10. Goal, objectives, and information needs for Subregion 2

4. What will be the "ecological" consequences associated with changes in regulation schedule?

▸ Develop a family of models and conduct associated field monitoring to assess potential impacts to vegetation, fish, wading birds, and snail kites resulting from changes in lake stage.

5. What are alternative water delivery mechanisms to create a littoral zone on the northwest end of Lake Okeechobee? (e.g., reconfigure Paradise Run)

▸ Develop models of various water delivery scenarios.

6. What is the feasibility of conveying predrainage flows from Lake Okeechobee south to the Everglades?

▸ Investigate the use of both operational methods and structural modifications (i.e., enlargement of maximum conveyance capacity in channels and pumps) to eliminate regulatory releases from Lake Okeechobee to the St. Lucie and Caloosahatchee canals and substantially increase delivery of water from Lake Okeechobee to the WCAs.

Ecological Restoration

Objectives

▸ Minimally, expand Lake Okeechobee's littoral zone by 200 km^2 (77 mi^2) on the northwest side and allow for increased water levels, consequently hydrologically integrating the lake and the Kissimmee River. Maximum restoration requires reestablishing the total lost littoral zone present prior to drainage and flood protection works.

▸ Integrate the islands at the southern end of the lake into an overall lake management plan.

▸ Eliminate (maximum) or control (minimum) exotic species from the Lake Okeechobee littoral zone.

▸ Reduce nutrient inputs to Lake Okeechobee to predisturbance levels; restore the lake's natural trophic status and phosphorus-limited condition; reduce algal bloom frequency, intensity, and composition to natural conditions.

▸ Eliminate (maximum) or reduce (minimum) point and nonpoint sources of pollution to Lake Okeechobee to meet Class I/III water quality standards.

▸ Restore Lake Okeechobee water quality, basin land-use characteristics, and littoral zone to predisturbance conditions for enhancement of wading bird, waterfowl, and threatened/endangered populations.

▸ Establish and maintain a recreational and commercial fishery that is consistent with the natural water quality and biological productivity of a restored Lake Okeechobee.

Critical questions and approaches.

Note: All questions and associated approaches were formulated under the assumption that a portion of the northwestern dike would be removed and the littoral zone would expand into this area.

1. What will be the spatial extent and hydrologic character of the expanded littoral zone along the northwest shoreline?

Prior to changing the configuration of the Northwest levee, the spatial extent and hydrology of the expanded littoral zone under the range of lake regulation schedules must be known. This information can be obtained by integrating proposed additions to the littoral zone into existing surface water models. The first step will be to conduct a grid-based topographic survey in the area behind the existing levee. Using this information, expected water depths and hydroperiods over the entire littoral zone can be determined over a range of lake stage, rainfall, and routing scenarios.

- Conduct a grid-based topographic survey of northwest area behind the Herbert Hoover Dike.

- Incorporate this area into grid-based spatial hydrologic models.

- Integrate output from the hydrologic models into GIS databases.

2. What are the water quality impacts associated with changes lake stage and littoral zone configurations?

Water quality has been the major focus of science activities in Lake Okeechobee. Existing water quality monitoring efforts in the lake should be enhanced to include the expanded littoral zone. Using data from past and ongoing monitoring efforts, models of phosphorus transport from open water sediment to the littoral zone should be developed. Additional models of water movement and phosphorus transport over the range of lake stage and littoral zone configurations should be developed. Output from these models can be used to develop specific recommendations on the configuration and water delivery to an expanded littoral zone.

- Develop models of phosphorus transport from sediments in the open water to the littoral zone.

- Develop hydrologic models to investigate potential for nutrient input via lake water to areas in the existing littoral zone that are isolated from eutrophic water.

3. How will vegetative and animal communities respond in the expanded littoral zone?

Hydrology is the dominant forcing function on littoral zone vegetative and animal communities. Because of the diversity in the littoral communities a range of ecosystem attributes should be modeled and monitored. The Science Subgroup recommends using, at a minimum, vegetation, game and nongame fish, wading birds, and snail kites as ecological endpoints in modeling and monitoring efforts. A GIS modeling and data management approach is the only feasible method of managing the data layers required. Using output from the spatial hydrologic and nutrient-transport models as templates, additional modules should be developed to investigate vegetative community types and the spatial distribution and dynamics expected to develop in the expanded littoral zone. These models should be designed to incorporate management options such as lake stage regulation and prescribed fire.

Once hydrology and vegetation models are developed, additional models of responses of various animal communities to changes in configuration, extent, composition, and hydrology of the littoral zone should be developed. Again, these models can be used to investigate impacts of various management actions on animal communities. Once the expanded littoral zone is established, long-term monitoring of vegetative and animals communities should be conducted. This will provide basic information on relationships between forcing functions (hydrology, fire, drought, etc.) and response endpoints (vegetation, wading birds, etc.). Statistical relationships between forcing functions and key ecosystem attributes can be refined. Long-term monitoring will also provide critical information to determine if ecological restoration goals are being met. These monitoring programs should be integrated with those developed for other subregions in the South Florida Ecosystem. The Science Subgroup recommends monitoring vegetation, game and nongame fish, wading birds, and snail kites as part of an integrated approach to evaluate success of restoring part of the littoral zone. These monitoring efforts will supplement the water quality and algal community monitoring programs outlined in the Lake Okeechobee Research Plan (SFWMD 1993).

- Develop models of vegetative community response to hydrologic conditions in littoral zone.

- Develop models of the responses of fish, wading birds, and snail kites to predicted hydrologic and vegetative conditions in the littoral zone.

- Develop and implement long-term monitoring programs at appropriate spatial and temporal scales for vegetation, fish, wading birds, and snail kites in the littoral zone.

4. What will be the impacts on the southern islands under different regulation schedules?

The approach would be the same as for the expanded littoral zone. Topographic data for the islands should be integrated into existing hydrologic models. The output from these models can be used to determine potential impacts under different regulation schedules so as not to negatively impact these areas.

- Conduct a grid-based topographic survey of islands in the southwest portion of the lake.
- Incorporate these islands into grid-based spatial hydrologic and nutrient-transport models.
- Integrate output from the hydrologic models into GIS databases.

5. What are the impacts of exotic plants on the Lake Okeechobee system and how can these impacts be mitigated?

The first step is to determine the distribution of exotic plant species. Next, relationships between lake stage, altered fire regime, water quality, and distribution/abundance of exotics should be determined via gradient analysis. This will provide information useful in understanding the mechanisms associated with dispersal, establishment, and maintenance of exotic plant communities. A better understanding of the distribution and density patterns of exotic plants can also be used to predict potential impacts to fish and wildlife habitats. This will provide information needed to help develop a priority list for species to control. The next step is to develop control mechanisms for those exotics that have the greatest impact on the system. Since the goal is to develop a sustainable system, development and implementation of biological control mechanisms should be given top priority. For example, the SFWMD has ongoing projects to investigate biocontrol mechanisms for melaleuca and the relationships between hydroperiod and growth of melaleuca seedlings (SFWMD 1993b).

- Map distribution of exotic plant species.
- Perform gradient analysis to determine controlling factors in distribution and spread of exotics.
- Develop a priority list of exotics to control.
- Develop biologic control mechanisms for all exotic species.

6. Are exotic and native fish competing for resources?

The habitat and dietary requirements of exotic fish in Lake Okeechobee need to be determined over the range of life stages. This will allow potential impacts to native species to be assessed.

- Conduct census surveys and feeding studies as necessary to assess resource partitioning between native and exotic fish.

7. What is the relative role of internal recycling vs. external loading in development of phytoplankton blooms?

This question is being addressed comprehensively in the SFWMD Lake Okeechobee Research Plan. This task is intended to reaffirm the need for this information.

- Collect data and analyze trends (spatial and temporal) in nutrient concentration, nutrient loading, and bloom development, composition, and magnitude.

8. What is the response of the aquatic invertebrate community to the changes in water/sediment quality?

Analysis of spatial and temporal trends in invertebrate community structure over the range of water/sediment quality conditions will provide information needed to assess impacts not only to invertebrates but also potential impacts to higher trophic levels. Existing chemical, physical, and biological data can be used to develop a stratified random sampling approach. This will allow rigorous statistical analysis to determine changes in invertebrate community structure and the causative factors.

▸ Collect data and perform gradient analysis on benthic invertebrate communities over the range of sediment type/quality.

9. What contaminants are likely to be impacting fish and wildlife communities?

A wide range of chemical contaminants has the potential to impact fish and wildlife communities in Lake Okeechobee. Due to the wide range of chemicals and effects, a systematic approach is needed to address potential effects. First, a list of contaminants most likely to impact fish and wildlife in the lake needs to be developed. Once this is done, appropriate studies can be designed to address the magnitude and extent of the problem. This process should be part of a system-wide reconnaissance.

▸ Develop a list of contaminants that warrant investigation.

▸ Acquire data on local, regional, and global sources; transport mechanisms; fate; and effects of these contaminants.

▸ Design appropriate monitoring programs (endpoints, methods, etc.) to assess extent and magnitude of impacts due to contaminants of concern.

BIBLIOGRAPHY

Ager, L.A., and K.E. Kerce. 1970. Vegetational changes associated with water level stabilization in Lake Okeechobee, Florida. Pages 338-351 *in* Proceedings of 24th Annual Conference of the Southeastern Association of Game and Fish Commissioners.

Aumen, N.G., and R.G. Wetzel, editors. 1995. Ecological studies on the littoral and pelagic systems of Lake Okeechobee, Florida (USA). Archiv für Hydrobiologie, Special Issues, Advances in Limnology 45.

Bierman, B.J., and R.T. James. 1993. A preliminary modeling analysis of phosphorus and phytoplankton dynamics in Lake Okeechobee, Florida: diagnostic and sensitivity analyses. SFWMD, West Palm Beach, Florida.

Browder, J., C. Littlejohn, and D. Young. 1976. South Florida: Seeking a Balance of Man and Nature. UF, Gainesville, Florida.

Burns, L.A., and I.R.B. Taylor. 1979. Nutrient-uptake model in marsh ecosystems. Journal of the Technical Councils of ASCE 105(TC1): 177-196.

Central and Southern Florida Flood Control District. 1975. Lake Okeechobee - Kissimmee basin proposals for management actions. SFWMD, West Palm Beach, Florida.

Collopy, M.W., and J.P. Smith. 1991. Patterns of distribution and abundance and the reproductive and foraging ecology of wading birds. Pages 242-330 *in* J.V. Shireman, editor. Ecological Studies of the Littoral and Pelagic Systems of Lake Okeechobee. Third Annual Report to the SFWMD, West Palm Beach, Florida.

David, P. 1993. Wading bird use of Lake Okeechobee relative to fluctuating water levels. SFWMD, West Palm Beach, Florida.

Davis, J.H. Jr. 1943. The natural features of southern Florida, especially the vegetation and the Everglades. Geological Bulletin No. 25. Florida Geological Survey, Tallahassee, Florida.

Dickson, K.G., A. Federico, and J.R. Lutz. 1978. Water quality in the Everglades Agricultural Area and its impact on Lake Okeechobee. SFWMD, West Palm Beach, Florida.

Dierberg, F.E. 1992. The littoral zone of Lake Okeechobee as a source of phosphorus after drawdown. Environmental Management 16(3):371- 380.

Dierberg, F.E. 1993. Decomposition of desiccated submersed aquatic vegetation and bioavailability of released phosphorus. Lake and Reservoir Management 8(1):31-36.

Flaig, E.G., and K.E. Havens. 1995. Historical trends in the Lake Okeechobee ecosystem I. Land use and nutrient loading. Archiv für Hydrobiologie Monographische Beitrage 107:1-24.

Fluck, R.C., C. Fonyo, and E. Flaig. 1992. Land-use-based phosphorus balances for Lake Okeechobee, Florida, drainage basins. Applied Engineering in Agriculture 8(6):813-820.

Gleason, P.J. 1984. Environments of South Florida Present and Past II. Miami Geological Society, Coral Gables, Florida.

Gunsalus, B., E.G. Flaig, and G. Ritter. 1992. Effectiveness of agricultural best management practices implemented in the Taylor Creek/Nubbin Slough Watershed and the Lower Kissimmee River Basin. SFWMD, West Palm Beach, Florida.

Havens, K.E. 1994. Seasonal and spatial variation in nutrient limitation in a shallow sub-tropical lake (Lake Okeechobee, Florida, USA) as evidenced by trophic state index deviations. Archiv für Hydrobiologie 131:39-53.

Havens, K.E. 1995. Relationships of annual chlorophyll *a* means, maxima and algal bloom frequencies in a shallow eutrophic lake (Lake Okeechobee, Florida, USA). Lake and Reservoir Management 10:127-132.

Havens, K.E. 1995. Particulate light attenuation in a large subtropical lake. Canadian Journal of Fisheries and Aquatic Sciences 52:1803-1811.

Havens, K.E. 1995. Secondary nitrogen limitation in a subtropical lake impacted by non-point source agricultural pollution. Environmental Pollution 89:241-246.

Havens, K.E. In press. Food web structure in a subtropical lake ecosystem. Oikos 75.

Havens, K.E., N.G. Aumen, R.T. James, and V.H. Smith. In press. Rapid ecological changes in a large subtropical lake undergoing cultural eutrophication. Ambio 25.

Havens, K.E., V.J. Bierman Jr., E.G. Flaig, C. Hanlon, R.T. James, B.L. Jones, and V.H. Smith. 1995. Historical trends in the Lake Okeechobee ecosystem. VI. Synthesis. Archiv für Hydrobiologie Monographische Beitrage 107:69-86.

Havens, K.E., T.L. East, R.H. Meeker, W.P. Davis, and A.D. Steinman. In press. Phytoplankton and periphyton responses to *in situ* experimental nutrient enrichment in a shallow subtropical lake. Journal of Plankton Research 18.

Havens, K.E., E.G. Flaig, R.T. James, S. Lostal, and D. Muszick. In press. Results of a program to control phosphorus discharges from dairy operations in south-central Florida, USA. Environmental Management.

Havens, K.E., C. Hanlon, and R.T. James. 1995. Historical trends in the Lake Okeechobee ecosystem. V. Algal blooms. Archiv für Hydrobiologie Monographische Beitrage 107:87-98.

Havens, K.E., C. Hanlon, and R.T. James. 1995. Seasonal and spatial variation in algal bloom frequencies in Lake Okeechobee, Florida, USA. Lake and Reservoir Management 10:133-138.

Havens, K.E., and B.H. Rosen. 1995. A plan for quantifying long-term ecological trends in Lake Okeechobee. Technical report. SFWMD, West Palm Beach, Florida.

Havens, K.E., and A.D. Steinman. 1995. Aquatic systems. Pages 121-151 *in* J.E. Rechcigl, editor. Soil Amendments: Impacts on Biotic Systems. Lewis Publishers, Boca Raton, Florida.

Johnson, L. 1958. A survey of the water resources of Everglades National Park, Florida. Lamar Johnson, Consulting Engineer, Lake Worth, Florida.

Johnson, L. 1974. Beyond the Fourth Generation. UF, Gainesville, Florida.

Koch, M.S., and K.R. Reddy. 1992. Division S-4--soil fertility & plant nutrition. Soil Science Society of America Journal 56:1492-1499.

Lake Okeechobee Technical Advisory Committee (LOTAC-I). 1986. Final report of the Lake Okeechobee Technical Advisory Committee. Submitted to the FDER, Tallahassee, Florida.

Lake Okeechobee Technical Advisory Council (LOTAC-II). 1990. Final report to the Governor of the State of Florida, Secretary of the Department of Environmental Regulation and Governing Board of The South Florida Water Management District. SFWMD, West Palm Beach, Florida.

Maceina, M.J., and D.M. Soballe. 1990. Wind-related limnological variation in Lake Okeechobee, Florida. Lake and Reservoir Management 6(1):93-100.

McIvor, C.C., and J.P. Smith. 1992. Patterns of distribution and abundance and the reproductive and foraging ecology of wading birds. Pages 118-234 *in* J.V. Shireman, editor. Ecological Studies of the Littoral and Pelagic Systems of Lake Okeechobee. Fourth Annual Report to the SFWMD, West Palm Beach, Florida.

Meyer, F.W. 1971. Seepage beneath Hoover Dike Southern Shore of Lake Okeechobee, Florida. Report of Investigations No. 58. USGS, Tallahassee, Florida.

Miller, S.J., G.L. Warren, M.J. Vogel, J.G. Wullschleger, and L.J. Davis. 1990. Lake Okeechobee- Kissimmee River-Everglades resource evaluation project. FGFWFC, Okeechobee, Florida.

Parker, G.G., G.E. Ferguson, S.K. Love, and others. 1955. Water Resources of Southeastern Florida. GPO, Washington, DC.

Pfeuffer, R.J. 1988. Herbicide monitoring program for the active ingredient fluridone [Sonar$^{(R)}$]. Technical Publication 88-8. SFWMD, West Palm Beach, Florida.

Pfeuffer, R.J. 1989. Lake Okeechobee pesticide monitoring report, 1987. SFWMD, West Palm Beach, Florida.

Pfeuffer, R.J. 1991. Pesticide residue monitoring in sediment and surface water within the South Florida Water Management District Volume 2. SFWMD, West Palm Beach, Florida.

Phlips, E.J., F.J. Aldridge, and C. Hanlon. 1994. Review of a seventeen year chlorophyll record as it pertains to the trophic status of Lake Okeechobee, Florida, USA. SFWMD, West Palm Beach, Florida.

Scheidt, D.J., M.D. Flora, and D.R. Walker. 1989. Water quality management for Everglades National Park. Pages 377-390 *in* D.W. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Sincock, J.L. 1957. Vegetation analysis procedure and detailed data. Appendix D *in* A Study of the Vegetation on the Northwest Shore of Lake Okeechobee: Its Frequency, Distribution, Ecology, Wildlife Values, and Predicted Distribution by Elevation with Proposed Water Control Measures. FGFWFC.

Smith, J.P. 1995. Foraging sociability of nesting wading birds (Ciconiiformes) at Lake Okeechobee, Florida. Wilson Bulletin 107(3):437-451.

Smith, V.H., V.J. Bierman Jr., B.L. Jones, and K.E. Havens. 1995. Historical trends in the Lake Okeechobee ecosystem. IV. Nitrogen:phosphorus ratios, cyanobacterial dominance, and nitrogen fixation potential. Archiv für Hydrobiologie Monographische Beitrage 107:69-86.

South Florida Water Management District. 1989. Surface water improvement and management plan for Lake Okeechobee. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1990. Lake Okeechobee water quality monitoring program annual report year five October 1987 - September 1988. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1993a. Lake Okeechobee Research Plan. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1993b. Surface Water Improvement and Management Plan. Update for Lake Okeechobee. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1993c. Draft working document in support of the Lower East Coast Regional Water Supply Plan. SFWMD Planning Department, West Palm Beach, Florida.

South Florida Water Management District. 1993d. Estuary Research Plan. Kissimmee and Okeechobee Systems, Department of Research, SFWMD, West Palm Beach, Florida.

Toth, L.A., and N.G. Aumen. 1993. Integration of multiple issues in environmental restoration and resource enhancements projects in south central Florida. SFWMD, West Palm Beach, Florida.

U.S. Army Corps of Engineers. 1949. Comprehensive Report on Central and Southern Florida for Flood Control and Other Purposes. GPO, Washington, DC.

U.S. Army Corps of Engineers. 1991. Simulation model of south central Florida hydrologic ecosystem. Reconnaissance Report. COE, Jacksonville, Florida.

Walker, W.W. Jr., and K.E. Havens. 1995. Relating algal bloom frequencies to phosphorus concentrations in Lake Okeechobee. Lake and Reservoir Management 11:77-83.

SUBREGION 3:

UPPER EAST COAST-ST. LUCIE RIVER AREA

INTRODUCTION

The Upper East Coast includes St. Lucie County, Martin County, and the northern part of Palm Beach County (Figure 1). The physiography of the area is dominated by a ridge-and-swale, terrace-and-bar topography created by a sequence of Pleistocene marine transgressive episodes (Parker et al. 1955). This geologic history has created the terraced structure of the land, the physiognomy of the river valleys, and the extensive lagoons -- the Indian River Lagoon System and Lake Worth -- characteristic of the coastal zone in this region.

The Atlantic Coastal Ridge is the most densely settled physiographic zone both here and to the south, with the barrier islands of the Atlantic Beach Ridge alternating between relatively protected park lands and extensive development, most notably in Palm Beach. The natural watersheds of watercourses in the region, including the St. Lucie and Loxahatchee rivers, are largely defined by relict dune lines and eroded marine terraces, albeit much modified by canals and drainage.

The coastal lagoons are locally regarded as an important estuarine resource of aesthetic, economic, recreational, and biological value. Much of Subregion 3 is included in the Indian River Lagoon National Estuary Program.

BACKGROUND AND MAJOR ISSUES

Before drainage and development, the coastal lagoons were more isolated from the Atlantic Ocean and received freshwater inflow in a pattern very different from today's. Prior to about 1880, the entire Indian River Lagoon was connected to the Atlantic by perhaps only three natural inlets: Ponce de Leon (near New Smyrna Beach), Fort Pierce, and Jupiter. The Fort Pierce Inlet, then located about 6.4 km (4 mi) north of today's constructed inlet, apparently underwent a periodic shift from the mouth of the Sebastian River south to the vicinity of Fort Pierce. In 1880, the St. Lucie River, as a defining example, was very different from today's estuarine system. The St. Lucie was then a freshwater system discharging into the southern end of Indian River Lagoon, with its closest connection to the Atlantic some 40 km (25 mi) to the north at the natural Fort Pierce Inlet. In 1892, the first artificial St. Lucie Inlet was opened, restoring a local connection to the Atlantic that had not been a feature of the system since the early 1800s. This began a transformation (or restoration, depending on the breadth of historical perspective employed) of the St. Lucie from a freshwater to an estuarine system.

The picture that emerges for all the Atlantic coastal lagoons (Mosquito, Banana River, Indian River, and Lake Worth) is thus one of ecosystems undergoing long-period shifts (at the present sea-level stand) between estuarine and freshwater character. Only perhaps three to five inlets could be sustained at any one time from tidal exchange energies and freshwater scour. These inlets were constantly shoaling and migrating along the coast, creating new interior freshwater flow paths along the north-south axis and depositing sediment to build deltaic "narrows" in the lagoons. At times the lagoons have been entirely fresh. Lake Worth was first noted on an 1830 map as a freshwater lake with drainage from a swampy area along its western edge (Pierce 1970); both its present Atlantic inlets are artificial (Palm Beach DERM 1990).

The opening of each artificial inlet robbed transport energy from the others. For example, when St. Lucie Inlet was dug and stabilized to keep it open, the natural Fort Pierce Inlet shoaled and closed; Fort Pierce Inlet was reconstructed in its present location in the 1920s. In the Pecks Lake area between Jupiter and St. Lucie inlets, additional inlets have continued to open and close, most recently in 1943 and 1962. The 1962 opening was closed by the COE because of shoaling problems it caused at St. Lucie Inlet. In sum, all inlets in the system are now artificially stabilized and must be maintained by periodic dredging.

Construction of the Atlantic Intracoastal Waterway, designed to provide safe passage to waterborne transport from Maine to Key West, further modified the hydraulics of these lagoons. The AIW is a deepwater (4 m) dredged channel in an otherwise shallow (1-2 m) system. It acts both as a sediment trap and as a conduit for penetration of more saline (denser) ocean water into the lagoons. Additional hydraulic modification, in the form of reduced longitudinal transport, was introduced by construction of access roads between the mainland and the barrier islands. The first bridges were of wood, constructed on pilings, and had little effect on circulation in the lagoons. These were replaced by fill causeways, pierced by narrow openings spanned by drawbridges, splitting the lagoons into hydraulically isolated sections. As drawbridges are replaced with fixed high-rise bridges, some of the problems are being corrected, both by widening the central spans and by construction of gaps in the causeways, spanned by "relief bridges," near their landward ends.

The terrestrial hydrology of Subregion 3 has been affected by drainage works for agricultural and residential development, flood control, and water supply. The primary canals are the C-23, C-24, C-25 system in St. Lucie and Martin counties; C-44 (St. Lucie Canal, connecting Lake Okeechobee to the Atlantic); C-18 complex in the Loxahatchee basin; and C-51 (West Palm Beach Canal), which discharges into Lake Worth. Because of the seasonality of rainfall and low-relief terrain, drainage works typically shorten and sharpen the hydroperiod, here as elsewhere in South Florida. Much of the area has been developed for citrus culture and range and pasture land, to a total of some 184,000 acres (287 mi^2) in the combined C-23, C-24, and C-25 basins. Of these, 46% (82,000 acres; 128 mi^2) require irrigation water.

As development has proceeded, conflicting water resource demands have become steadily more sharply contested. Several resulting actions have begun the process of resolving water allocation and management conflicts. The impacts of C-44 regulatory releases from Lake Okeechobee on the St. Lucie estuary may ultimately be ameliorated somewhat by institution of the Run 25 regulation schedule (Trimble and Marban 1988). The need to protect the West Palm Beach urban wellfield recharge zone and the Loxahatchee Wild and Scenic River watershed has encouraged reclamation of Hungryland Slough and more sophisticated management of the C-18 Canal complex in the southern Loxahatchee basin. (South of C-18, the Biscayne Aquifer is the primary water source for Palm Beach County.) If concerns about quick-response floodwater removal capacity can be resolved, water levels in the C-23-24-25 canals might be held at higher stages, in an apparent consensus decision that the environmental harm done by lowered water tables seems to outweigh their incremental contribution to effective flood protection. The SOR program purchased the DuPuis Reserve in 1986 (David 1991) and has included a variety of area lands in the SOR planning process. A notable feature of the sequence of purchases is the potential systematic restoration of hydrologic and habitat continuity in the Loxahatchee watershed, to include the DuPuis Reserve, Corbett Wildlife Management Area, Pal-Mar, Loxahatchee Slough and Reserve, and West Palm Beach water catchment area. Inclusion of natural water quality restoration zones at the western end of C-51, as provided in recent State legislation, will begin to address the impacts of C-51 on Lake Worth.

Fundamental problems remain to be solved, however, despite growing dialogue among agricultural, natural resource management, residential development, and governmental institutions in Subregion 3. As elsewhere in South Florida, lack of adequate tools and knowledge for evaluating ecological, economic, and social consequences of water management alternatives is the most important impediment to consensus and action for achieving a sustainable future for the area. One aspect of the problem is unique to this area, however. The ecological future envisioned for the Atlantic coastal lagoons is that of a stable estuarine system, rather than the historical pattern of alternating freshwater aquatic and maritime regimes. The hydrologic management puzzle in this subregion is thus an ecosystem design challenge, rather than simply a resource allocation problem.

One primary objective in the redesign of this landscape is to foster creation of healthy estuarine lagoons by restoring freshwater base flows and eliminating massive peak flood-control flows to the system. The best mixture of landscape alterations to achieve this end is far from obvious. Raising canal stages benefits wetlands and increases landscape detention and base flow. Issues then arise of impacts on agricultural productivity (which differ among uses; e.g., citrus vs. pasture) and loss of flood-control capacity. Detention storage -- the capacity of the landscape to hold rainfall on and near the surface and release it over an extended period -- was once an intrinsic property of the low-relief terrain in this historically hydric landscape. This function can be partially restored in today's mesic landscape by building Regional Attenuation Facilities (i.e., constructed reservoirs) and their smaller analogues (Small Attenuation Facilities) spread throughout the drainage network. It has been proposed that the C-23-24-25

canal complex be physically connected to Lake Okeechobee, drawing upon the lake's capacity as a regional reservoir or ultimate RAF. In this circumstance, waters that would otherwise be discharged to tide could in principle be metered to the restored wetlands of the Loxahatchee and other wetland complexes, thus rebuilding a significant portion of the subregion's natural hydrologic function. Each of these options -- RAFs, SAFs, canal water-level management, and the proposed connection to Lake Okeechobee -- has been the subject of recent studies (Spyke, pers. comm.). Whether Lake Okeechobee could serve such a role without harm to itself is not apparent; this issue should be addressed in the context of studies on the restoration ecology of the lake ecosystem. The issue of the relative value or weight to be given potential harm to Okeechobee ecosystems, against gain to estuarine ecosystems from restoration of a less polyhaline salinity regime, will not easily be resolved.

Current rules of both the SFWMD and SJRWMD require SAF installation on new urban and agricultural projects. This policy avoids exacerbating the current problem and may be providing some incremental improvements. Structures have been added to canals to increase water levels, improving water supply and increasing detention flows from storage in the shallow groundwater. The SFWMD is currently conducting watershed modeling (HSPF) studies to investigate the relative merits and balance among the options of SAFs, RAFs, implementation of BMPs, and changes in regulations (Haunert, pers. comm.; Labadie 1995).

These changes, however, cannot fully compensate for loss of wetland structure that has already occurred as the region developed, and "retrofitting" every parcel of land in the subregion is not a feasible alternative. Thus, RAFs and access to storage capacity in Lake Okeechobee (with the caveat that the ability of the lake to accommodate this usage is unproven) appear to be necessary additions to current approaches to restoring regional hydrologic function. In one proposal, a large RAF would be built at the western end of C-23 or C-24 and connected to Lake Okeechobee; this RAF would serve as a detention basin and water quality improvement facility to ensure that nutrient or pollutant loads are not imposed on the lake as a cost of restoration of the coastal lagoons and intervening wetlands.

CURRENT SCIENTIFIC STUDIES

Because much of Subregion 3 is included in the IRLNEP, a substantial science planning and coordination effort is already underway. In addition, the IRL is the subject of SWIM planning coordinated between the SFWMD and SJRWMD. An inventory of science and management studies begun prior to July 1987 was published in the 1988 Interim SWIM Plan for the Indian River Lagoon (SJRWMD/SFWMD 1988) and Indian River Lagoon Joint Reconnaissance Report (Steward and Van Arman 1987). A survey of studies conducted for the period July 1987 through 1989 is given in Appendix C of the 1989 Indian River Lagoon SWIM Plan (SJRWMD/SFWMD 1989), and a description of studies initiated after July 1990 is given in Appendix C of the SWIM Plan Update for the Indian River Lagoon (Steward et al. 1993). Appendix F of the 1993 document also includes detailed summaries of 22 ongoing projects in the five SWIM programs for the IRL:

- Water and Sediment Quality (12 Projects)
  - Water quality monitoring network: point and nonpoint pollution source assessment.
  - Toxic substances monitoring network.
  - Muck sediment identification and control.
  - Nutrient loadings assessment.
  - Turkey Creek watershed management plan.
  - Sebastian River watershed management plan.
  - Stormwater management.
  - Hydrologic and hydrodynamic monitoring/modeling.
  - Land cover mapping for nonpoint source identification.
  - Pathogen sources ID and control.
  - St. Lucie County management project.
  - Martin County management project.

- Habitat Preservation and Restoration (3 projects)
  - Seagrass preservation/restoration.
  - Wetlands restoration/preservation.
  - Land acquisition.
- Regulation and Enforcement (3 projects)
  - Inventory of gravity-drained agricultural runoff and assessment of water quality impacts.
  - Stormwater research and rule development: design guidelines and criteria for retention with filtration systems.
  - Increased investigation and enforcement of on-site sewage disposal systems, point source discharges, and stormwater treatment systems.
- Public Awareness Program (1 project)
  - Public awareness program.
- Administration, Planning, and Coordination (3 projects)
  - Indian River Lagoon databases.
  - Indian River Lagoon scientific information system.
  - Plan development.

Project IR-4-501-S is developing a computerized database repository for hydrologic, hydrodynamic, water quality, sediment, and biological data for the IRL. The SWIM program will rely heavily on the Data and Information Management Strategy presently in development under the direction of IRLNEP and a DIMS committee, which includes representatives from the SJRWMD and SFWMD. DIMS will coordinate retrieval and exchange of water quality data primarily, and then other types of data (including GIS) as DIMS matures. Available datasets have been enumerated for the St. Lucie Estuary by Mahadevan and Lowrey (1993).

IRLNEP Project Summaries for Fiscal Years 1991-1995, as provided by the NEP, are presented in Appendix B to this chapter.

INFORMATION NEEDS

The goal, objectives (based on SSG 1993), and information needs for Subregion 3 are summarized in Figure 11. Information needs specifically related to several important issues are outlined below.

Sources of Fine-Grained Organic Sediments

Water and sediment quality in the coastal lagoons and estuaries is viewed as problematic due to accumulation of significant deposits of fine-grained organic ooze on the bottom at many localities. Some of these deposits carry significant contaminant loads (Trefry et al. 1992, Trocine and Trefry 1993, Vereecke 1993). Although a variety of proposals to deal with the problem has been investigated, no action can currently be undertaken in full confidence of improving the situation, due to lack of adequate understanding of the source and transport dynamics of the materials. Some of the deposits appear to be of considerable age, although whether they were deposited as mobilized terrigenous materials from canal construction or from recent activity in the watersheds is uncertain. Studies need to be undertaken to identify the source of the material (aquatic plants derived directly from the canals, dissolved organics of wetland origin precipitating at the salt interface, canal bank and construction debris, etc.) and the conditions driving transport and deposition to better plan control measures.

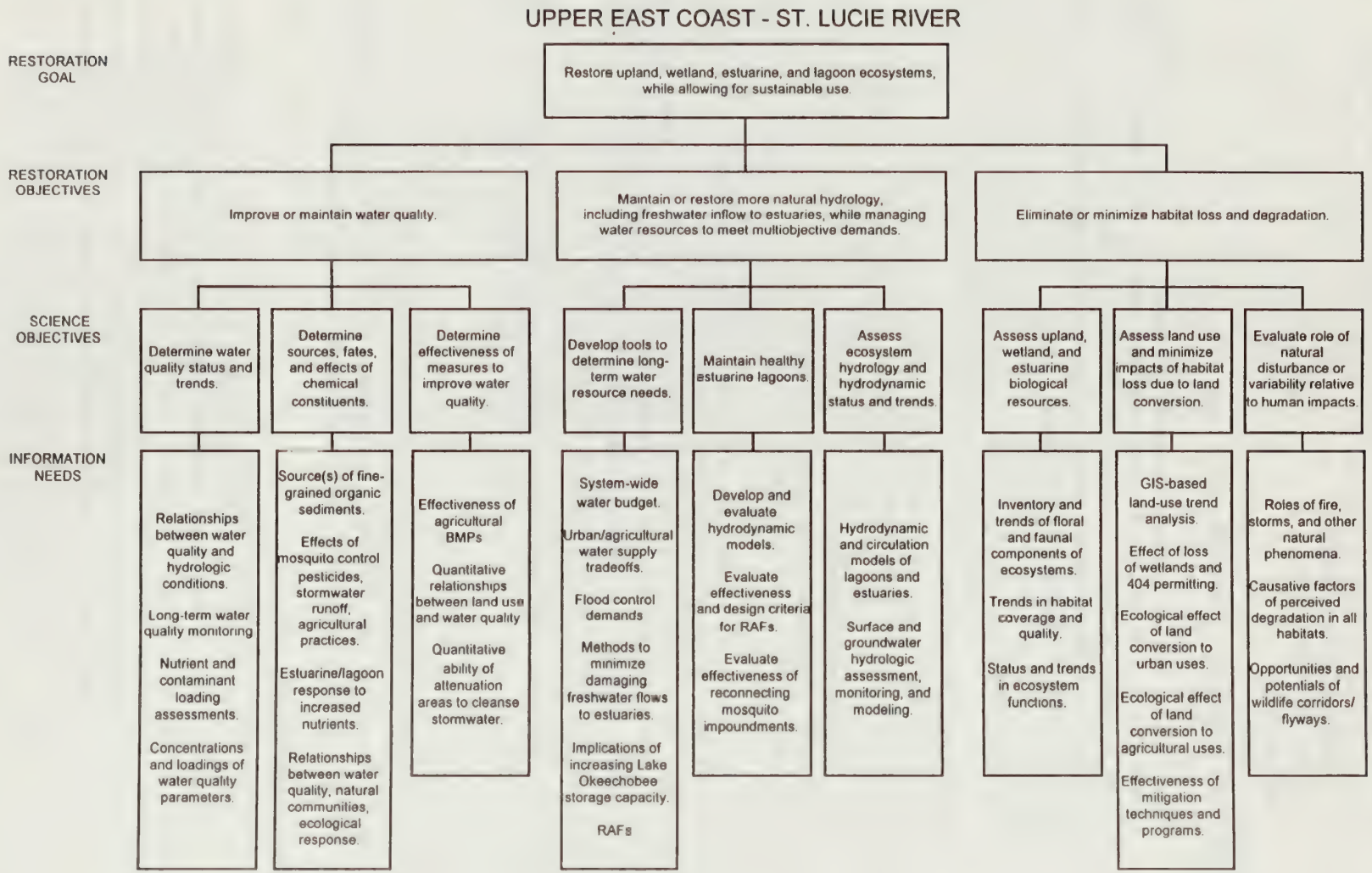

UPPER EAST COAST - ST. LUCIE RIVER
RESTORATION GOAL
Restore upland, wetland, estuarine, and lagoon ecosystems, while allowing for sustainable use.
RESTORATION OBJECTIVES
Improve or maintain water quality.
Maintain or restore more natural hydrology, including freshwater inflow to estuaries, while managing water resources to meet multiobjective demands.
Eliminate or minimize habitat loss and degradation.
SCIENCE OBJECTIVES
Determine water quality status and trends.
Determine sources, fates, and effects of chemical constituents.
Determine effectiveness of measures to improve water quality.
Develop tools to determine long-term water resource needs.
Maintain healthy estuarine lagoons.
Assess ecosystem hydrology and hydrodynamic status and trends.
Assess upland, wetland, and estuarine biological resources.
Assess land use and minimize impacts of habitat loss due to land conversion.
Evaluate role of natural disturbance or variability relative to human impacts.
INFORMATION NEEDS
Relationships between water quality and hydrologic conditions.
Long-term water quality monitoring
Nutrient and contaminant loading assessments.
Concentrations and loadings of water quality parameters.
Source(s) of fine-grained organic sediments.
Effects of mosquito control pesticides, stormwater runoff, agricultural practices.
Estuarine/lagoon response to increased nutrients.
Relationships between water quality, natural communities, ecological response.
Effectiveness of agricultural BMPs
Quantitative relationships between land use and water quality
Quantitative ability of attenuation areas to cleanse stormwater.
System-wide water budget.
Urban/agricultural water supply tradeoffs.
Flood control demands
Methods to minimize damaging freshwater flows to estuaries.
Implications of increasing Lake Okeechobee storage capacity.
RAFs
Develop and evaluate hydrodynamic models.
Evaluate effectiveness and design criteria for RAFs.
Evaluate effectiveness of reconnecting mosquito impoundments.
Hydrodynamic and circulation models of lagoons and estuaries.
Surface and groundwater hydrologic assessment, monitoring, and modeling.
Inventory and trends of floral and faunal components of ecosystems.
Trends in habitat coverage and quality.
Status and trends in ecosystem functions.
GIS-based land-use trend analysis.
Effect of loss of wetlands and 404 permitting.
Ecological effect of land conversion to urban uses.
Ecological effect of land conversion to agricultural uses.
Effectiveness of mitigation techniques and programs.
Roles of fire, storms, and other natural phenomena.
Causative factors of perceived degradation in all habitats.
Opportunities and potentials of wildlife corridors/ flyways.

Figure 11. Goal, objectives, and information needs for Subregion 3.

Three-Dimensional Regional Hydrologic Model

This project would constitute one thread of a spatial decision-support capability needed to begin a process of multi-institutional planning for regional landscape management. It would be based in hydrologic modeling of the surface and groundwater resources of the region. Its capabilities and data needs include, *inter alia*:

- Complete, and accurate, regional water budgeting.
- Accurate flood and discharge profiles for canals and structures in the region, including a capability to evaluate consequences of structure modifications.
- Capability to evaluate impact of current and proposed secondary structures (e.g., weirs in feeder canals), including a capability to evaluate consequences of structure modifications.
- Groundwater recharge and withdrawal scheduling.
- Water recycling and re-use initiatives within the basin.
- Ability to accept weather service forecast and stage monitoring data, and respond with appropriate infrastructure operations schedules.
- Ability to track actual response (stage, discharge, water quality data) to continually recalibrate empirical and process-based response functions--for both quantity and quality parameters, including turbidity, DO, nutrient loads, soft sediment remobilization and transport, and industrial, domestic, and agricultural toxic substances loadings.

One of the critical design criteria for this modeling system would be that it assist in placement and operation of RAFs, SAFs, canal structures, hydrologic exchanges with Lake Okeechobee, and water releases to support ecological and economic functions of the regional landscape. Although current and developing policies in Subregion 3 are certainly "directionally correct," the inability to evaluate the full costs and benefits of alternative scenarios impedes consummation of the political and economic consensus needed to move forward with restoration.

Hydrodynamic Models

Hydrodynamic models of the lagoons are needed to understand and forecast effects of hydrologic management on water quality, salinity regime, sediment quality and deposition, turbidity and color, and circulation. The permanent linkage of the lagoons to the Atlantic Ocean mandates scientific investigation of:

- Flow on the shelf and net transport in the inlets in order to understand larval transport and water quality interactions between the lagoons and the open ocean.
- Salinity and circulation patterns in relation to freshwater inflow.
- Hydrodynamics of the entire lagoon cross-section (i.e., AIW and shallow margins).

The resulting model systems can be used to forecast effects of hydrologic manipulations on the lagoons. Once confidence in the models is gained, they can be used to evaluate possible engineering changes in design and maintenance of the inlets that could improve water quality, benthic sediment quality, habitat condition, and ecosystem health in the lagoons.

Ecological Response Models

Ecological response models linked to the hydrologic, water quality, and hydrodynamic models are needed to forecast biological responses to hydrologic management alternatives. In addition to the general capabilities envisioned for the restoration project as a whole, ecological information needs for Subregion 3 include:

- Evaluation of salinity intrusion impacts on freshwater swamp forests.
- Salinity requirements of major benthic organisms and fishes.
- Modeling of the response of specific target populations (e.g., oysters) to estuarine salinity regimes (Haunert and Startzman 1980; Haunert and Startzman 1985, Appendix I: Draft St. Lucie Estuary Watershed Plan, in Steward et al. 1993).
- Management strategies for mosquito impoundments to enhance nursery functions for estuarine-dependent marine fauna and habitat value for bird populations.

Landscape Planning and Forecasting Models

The coherence and reliability of regional planning, conservation, and development efforts would be immensely enhanced by creation of a genuine landscape modeling capability for the Upper East Coast watersheds. Subregion 3 is an intricate landscape mosaic of wetland complexes. Residential, industrial and commercial development, park lands, and agricultural land uses occur in close proximity, and hydrologic and land management requirements often conflict in this complex mosaic. Formulation of consensus goals for a sustainable future will not succeed until all stakeholders can achieve reasonable certainty of adequate representation of their constituents' interests in the future landscapes of the subregion. Landscape planning models should be developed with capacity to reliably forecast natural resource, ecological, economic, and social consequences of engineering works, land-use changes, and hydrologic management policies. One primary design feature of these models should be an ability to fully analyze the consequences of placement within the landscape of a variety of RAFs and SAFs, the impact of proposed BMPs on agricultural lands, and the effects of alternative water management regulations and schedules.

Red Mangrove Culture

The red mangrove (*Rhizophora mangle*) has been artificially propagated in the lagoons and is a valuable contributor to the detrital food chain. Its adult height impairs the customary scenic visibility of waterfront property on the lagoons, however, and property owners are legally entitled to prune the trees. The impact of pruning has not been fully evaluated, although this species' frost intolerance suggests it may be only moderately tolerant of mechanical damage. Tolerances for pruning damage and horticultural procedures need to be established.

ACKNOWLEDGMENTS

In response to an invitation from the Science Subgroup, 17 scientists from organizations with interests in the Upper East Coast planning area gathered at the FWS office at Vero Beach on March 22, 1994. Participants presented their views of critical issues and scientific information needs in Subregion 3 and contributed written statements (Appendix A) to assist in preparation of this chapter. Gratitude is extended to these individuals and their organizations for their contributions; they of course bear no direct responsibility for the final product, although it would be the poorer absent their counsel.

BIBLIOGRAPHY

Adams, K. 1992. A three-dimensional finite difference ground water flow model of the surficial aquifer in Martin County, Florida. Technical Publication 92-02. SFWMD, West Palm Beach, Florida.

Allman, D.W., and G. Winter. 1976. C-51 leakage. Technical Memorandum DRE-67. SFWMD, West Palm Beach, Florida.

Bower, R.F. 1988. Permittable water use estimates of the Floridan aquifer system in the upper east coast planning area. SFWMD, West Palm Beach, Florida.

Brown, M.P., and D.E. Reece. 1979. Hydrogeologic reconnaissance of the Floridan aquifer system upper east coast planning area. Technical Map Series 79-1, DRE-94. SFWMD, West Palm Beach, Florida.

Cooper, R.M., and J. Lane. 1988. An atlas of eastern Palm Beach County surface water management basins. SFWMD, West Palm Beach, Florida.

Cooper, R.M., and T.W. Ortel. 1988. An atlas of St. Lucie County surface water management basins. Technical Memorandum DRE-265. SFWMD, West Palm Beach, Florida.

Cooper, R.M., and R. Santee. 1988. An atlas of Martin County surface water management basins. SFWMD, West Palm Beach, Florida.

David, P. 1991. DuPuis Reserve environmental assessment. SFWMD, West Palm Beach, Florida.

Dubois, B.W. 1981. The History of the Loxahatchee River. Southeastern Printing Company, Stuart, Florida.

Fan, A. 1985. Rainfall drought frequency and availability of surface water in Martin County. SFWMD, West Palm Beach, Florida.

Federico, A.C. 1983. Upper East Coast water quality studies. Technical Publication 83-1. SFWMD, West Palm Beach, Florida.

Graves, G.A., and D.G. Strom. 1992. Bessey Creek and the greater St. Lucie estuary: a biological and physico-chemical analysis. FDER, Port St. Lucie, Florida.

Haunert, D.E. 1988. Sediment characteristics and toxic substances in the St. Lucie estuary, Florida. Technical Publication 88-10. SFWMD, West Palm Beach, Florida.

Haunert, D.E., and J.R. Startzman. 1980. Some seasonal fisheries trends and effects of a 1000 cfs fresh water discharge on the fishes and macroinvertebrates in the St. Lucie estuary, Florida. Technical Publication 80-3. SFWMD, West Palm Beach, Florida.

Haunert, D.E., and J.R. Startzman. 1985. Short term effects of a freshwater discharge on the biota of St. Lucie estuary, Florida. Technical Publication 85-1. SFWMD, West Palm Beach, Florida.

Hopkins, E. 1991. A water resource analysis of the Jensen Beach peninsula, Martin County, Florida. Technical Publication 91-03. SFWMD, West Palm Beach, Florida.

Indian River Lagoon National Estuary Program. 1993a. The Preliminary Comprehensive Conservation and Management Plan for the Indian River Lagoon. IRLNEP, Melbourne, Florida.

Indian River Lagoon National Estuary Program. 1993b. The summary for the Comprehensive Conservation and Management Plan for the Indian River Lagoon. IRLNEP, Melbourne, Florida.

Labadie, J.W. 1995. Optimization of managed runoff to the St. Lucie Estuary. Final report (PO# PC-P60617) to Upper District Planning Division, SFWMD, West Palm Beach, Florida.

Lukasiewicz, J. 1992. A three-dimensional finite difference ground water flow model of the Floridan aquifer system in Martin, St. Lucie and eastern Okeechobee Counties, Florida. Technical Publication 92-03. SFWMD, West Palm Beach, Florida.

Mahadevan, K., and S. Lowrey. 1993. St. Lucie Estuary nutrient loading assessment. Technical Report 307. Mote Marine Laboratory, Sarasota, Florida.

McPherson, B.F., and M. Sabanskas. 1980. Hydrologic and land-cover features of the Loxahatchee river basin, Florida. Water-Resources Investigations Open-File Report 80-1109. USGS, Tallahassee, Florida.

McPherson, B.F., M. Sabanskas, and W.A. Long. 1982. Physical, hydrological, and biological characteristics of the Loxahatchee River estuary, Florida. Water-Resources Investigations Open-File Report 82-350. USGS, Tallahassee, Florida.

Morris, F.W. 1986. Bathymetry of the St. Lucie estuary. Technical Publication 86-4. SFWMD, West Palm Beach, Florida.

Morris, F.W. 1987. Modeling of hydrodynamics and salinity in the St. Lucie estuary. Technical Publication 87-1. SFWMD, West Palm Beach, Florida.

Nealon, D., G. Shih, S. Trost, S. Opalat, A. Fan, and B. Adams. 1987. Martin County water resource assessment. SFWMD, West Palm Beach, Florida.

Noel, J.M., and R.H. Chamberlain. 1993. Environmental factors influencing suspended solids in the Loxahatchee estuary, Florida. DOR Paper 117. SFWMD, West Palm Beach, Florida.

Opalat, S. 1985. Urban water demand estimates for Martin County: 1983 existing and committed, and buildout. SFWMD, West Palm Beach, Florida.

Padgett, D.G.J. 1987. One foot drawdown zones of influence surrounding municipal water supply wellfields in Palm Beach County. SFWMD, West Palm Beach, Florida.

Palm Beach County Department of Environmental Resources Management. 1990. Lake Worth Lagoon natural resources inventory and resource enhancement study. Palm Beach County DERM, West Palm Beach, Florida.

Palm Beach County Department of Environmental Resources Management. 1992. Palm Beach County, Florida estuarine natural resources inventory and resources enhancement study. Palm Beach County DERM, West Palm Beach, Florida.

Parker, G.G., G.E. Ferguson, S.K. Love, and others. 1955. Water Resources of Southeastern Florida with Special Reference to the Geology and Ground Water of the Miami Area. USGS Water-Supply Paper 1255. U.S. DOI, Washington, D.C.

Pierce, C.W. 1970. Pioneer Life in Southeast Florida. University of Miami Press, Coral Gables, Florida.

Resource Planning Department. 1984. Water management planning for the western C-51 basin, Palm Beach County, Florida. SFWMD, West Palm Beach, Florida.

Russell, G.M., and B.F. McPherson. 1984. Freshwater runoff and salinity distribution in the Loxahatchee River estuary, southeastern Florida, 1980-82. Water Resources Investigations Report 83-4244. USGS, Tallahassee, Florida.

Rutchey, K. 1992. The response of vegetation and benthic macroinvertebrates to constructed littoral habitat in Canal 51. Technical Memorandum DRE-306. SFWMD, West Palm Beach, Florida.

St. Johns River Water Management District and South Florida Water Management District. 1988. Interim SWIM Plan for the Indian River Lagoon, Appendices A-H. SJRWMD, Palatka, Florida, and SFWMD, West Palm Beach, Florida.

St. Johns River Water Management District and South Florida Water Management District. 1989 (revised). Surface Water Improvement and Management (SWIM) Plan for the Indian River Lagoon, Appendices A-H. SJRWMD, Palatka, Florida, and SFWMD, West Palm Beach, Florida.

Schropp, S.J., W.F. McFetridge, and R.B. Taylor. 1994. St. Lucie estuary muck removal demonstration project. Final report C-3269. Taylor Engineering, Inc., Jacksonville, Florida.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Shine, M.-J., D.G.J. Padgett, and W.M. Barfknecht. 1989. Ground water resource assessment of western Palm Beach County, Florida, Part II: plates and oversized appendices reduced to 8 1/2 x 11. Technical Publication 89-4. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1992. Water supply needs and sources 1990-2010. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1993. Estuary Research Plan. Kissimmee and Okeechobee Systems, Department of Research, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1994. Save Our Rivers Five Year Plan. SFWMD, West Palm Beach, Florida.

Steward, J., and J. Van Arman, editors. 1987. Indian River Lagoon joint reconnaissance report. SFWMD, West Palm Beach, Florida.

Steward, J., R. Virnstein, D. Haunert, and F. Lund, editors. 1993. Draft Surface Water Improvement and Management (SWIM) Plan for the Indian River Lagoon. SFWMD, West Palm Beach, Florida.

Trefry, J.H., N.-C. Chen, R.P. Trocine, and S. Metz. 1992. Impingement of organic-rich, contaminated sediments on Manatee Pocket, Florida. Florida Scientist 55:160-171.

Trimble, P., and J. Marban. 1988. Preliminary evaluation of the Lake Okeechobee regulation schedule. Technical Publication 88-5. SFWMD, West Palm Beach, Florida.

Trocine, R.P., and J.H. Trefry. 1993. Toxic substances survey for the Indian River Lagoon system (final report to the St. Johns River Water Management District and the Indian River Lagoon National Estuary Program). Marine and Environmental Chemistry Laboratories, Florida Institute of Technology, Melbourne, Florida.

Vereecke, R.M. 1993. Trace metal geochemistry in different sedimentary environments of a Florida estuary. Thesis. Florida Institute of Technology, Melbourne, Florida.

Wanless, H., V. Rossinsky Jr., and B.F. McPherson. 1984. Sedimentologic history of the Loxahatchee River estuary, Florida. Water Resources Investigations Report 84-4120. USGS, Tallahassee, Florida.

Water Use Planning and Management Staff. 1987. Western C-51 basin: Palm Beach County population and land use projections (1985-2040). SFWMD, West Palm Beach, Florida.

Woehlcke, C., and D.R. Loving. 1979 (1980). Non-agricultural water use in the upper east coast planning area. Memorandum Report DRE-92. SFWMD, West Palm Beach, Florida.

Woodward-Clyde Consultants. 1994a. Biological resources of the Indian River Lagoon (two volumes). Woodward-Clyde Consultants, Tampa, Florida.

Woodward-Clyde Consultants. 1994b. Historical imagery inventory and seagrass assessment, Indian River Lagoon. Woodward-Clyde Consultants, Tampa, Florida.

Woodward-Clyde Consultants. 1994c. Loadings assessment of the Indian River Lagoon. Woodward-Clyde Consultants, Tampa, Florida.

Woodward-Clyde Consultants. 1994d. Non-governmental and governmental programs for the Indian River Lagoon. Woodward-Clyde Consultants, Tampa, Florida.

Woodward-Clyde Consultants. 1994e. Physical features of the Indian River Lagoon. Woodward-Clyde Consultants, Tampa, Florida.

Woodward-Clyde Consultants. 1994f. Quality assessment of the Indian River Lagoon. Woodward-Clyde Consultants, Tampa, Florida.

Woodward-Clyde Consultants. 1994g. Uses of the Indian River Lagoon. Woodward-Clyde Consultants, Tampa, Florida.

APPENDIX A

RESEARCH NEEDS WORKSHOP

MARCH 22, 1994
VERO BEACH, FLORIDA

In response to an invitation from the Science SubGroup of the South Florida Restoration Interagency Working Group, 17 scientists from a variety of organizations with interests in the Upper East Coast planning area gathered at the U.S. Fish and Wildlife Service's conference facility at Vero Beach on March 22, 1994. The assembled group made formal and informal presentations of their views on scientific information needs and critical issues in Subregion 3, participated in discussions, and several contributed written statements to assist in the formulation of the Federal Science Plan for South Florida. Gratitude is extended to these individuals and their organizations for their contributions; they of course bear no direct responsibility for the final product, although deserving of credit for their contribution to such good qualities as it may possess. The written contributions submitted at the workshop are herein appended, following a complete list of those in attendance.

List of Participants

Kathleen M. Brennan
Palm Beach Co. Dept. Environ. Resource Manage.
3111 South Dixie Hwy, Suite 146
West Palm Beach, FL 33405
Tel 407-355-4011
Fax 407-355-4653

Harold F. Brown
N. St. Lucie River Water Control District
2721 S. Jenkins Road
Fort Pierce, FL 34981
Tel 407-461-5050
Fax 407-461-9446

Lawrence A. Burns
US EPA, ORD, ERL-Athens
960 College Station Road
Athens, GA 30605-2720
Tel 706-546-3511
Fax 706-546-3252

James R. David
St. Lucie Co. Mosquito Control District
2300 Virginia Avenue
Ft. Pierce, FL 34982
Tel 407-468-1692
Fax 407-468-1565

Robert A. Day
Indian River Lagoon Natl. Estuary Prog.
1900 South Harbor City Blvd, Suite 109
Melbourne, FL 32901-4749
Tel 407-984-4950
Fax 407-984-4937

Gregory A. Graves
Florida Dept. of Environmental Protection
1801 S.E. Hillmoor Drive
Port St. Lucie, FL 34982
Tel 407-871-7662
Fax 47-871-7666

Daniel E. Haunert
South Florida Water Management District
P.O. Box 24680
West Palm Beach, FL 33416-4680
Tel 407-687-6606
Fax 407-687-6442

Richard B. Hellstrom, P.E., Chief Engineer
N. St. Lucie River Water Control District
LBFH, Inc., 2222 Colonial Road, Suite 201
Fort Pierce, FL 34950
Tel 407-461-2450
Fax 407-465-1225

Frank Lund
South Florida Water Management District
P.O. Box 24680
West Palm Beach, FL 33416-4680
Tel 407-687-6631
Fax 407-687-6442

Doug Morrison
US Fish & Wildlife Service
P.O. Box 2676
Vero Beach, FL 32961-2676
Tel 407-562-3909
Fax 407-562-4288

Max Quackenbos
St. Lucie River Initiative
1778 N.W. Palmetto Terrace
Stuart, FL 34994
Tel 407-692-1451

Cathy Reeder
St. Lucie River Initiative
P.O. Box 2082
Stuart, FL 34995-2082
Tel 407-287-8326
Fax 407-287-8326

Richard E. Roberts
FL Park Service, Loxahatchee River W&S
P.O. Box 1246
Hobe Sound, FL 33455
Tel 407-744-9245
Fax 407-744-7604

Harvey Rudolph
Palm Beach County Dept. Environ. Resource Manage.
3111 South Dixie Hwy, Suite 146
West Palm Beach, FL 33405
Tel 407-355-4011
Fax 407-355-4653

Liberta Scotto
Florida Dept. Environmental Protection
1801 S.E. Hillmoor Dr., Suite C-204
Port St. Lucie, FL 34982
Tel 407 871-7662
Fax 407-871-7666

Donna M. Smith
USDA Soil Conservation Service
8400 Picos Road, Suite 202
Fort Pierce, FL 34945
Tel 407-461-4546
Fax 407-461-6923

Ned P. Smith
Harbor Branch Oceanographic Institution
5600 North U.S. Highway One
Ft. Pierce, FL 34946
Tel 407-465-2400 x 441
Fax 407-468-0757

Peter D. Spyke
President, Arapaho Citrus Management
13300 Okeechobee Road
Fort Pierce, FL 34945
Tel 407-464-3391
Fax 407-464-4170

RESEARCH NEEDS

SUB-REGION 2. LAKE OKEECHOBEE AND THE EAST/WEST WATERWAYS
AND
SUB-REGION 3. NORTH PALM BEACH, MARTIN, AND SOUTH ST. LUCIE COUNTIES

James R. David
St. Lucie Co. Mosquito Control District
2300 Virginia Avenue
Ft. Pierce, FL 34982

I. A PROPOSED SOLUTION TO THE FRESHWATER IMPACTS TO THE INDIAN RIVER LAGOON/SAINT LUCIE RIVER ESTUARY IS TO CONSTRUCT A REGIONAL ATTENUATION FACILITY (RAF), OR RESERVOIR, FOR THE C23, C24 AND C25 BASINS.

RESEARCH NEEDS

A. Develop hydrological models of the three basins which should include drainage needs, water supply needs, storage design requirements, Floridan aquifer water quality impacts and Inlet(s) flushing impacts.

B. Examine the environmental impacts of construction at the location of potential RAF sites.

C. Evaluate the ecological impacts of pre- and post-RAF construction vis-a-vis: fish deformities; oyster indicator envelope (where relevant); ooze and muck removal/transport; Photosynthetically Active Radiation (PAR)/light transmissivity and bathymetry as they are related to potential seagrass distribution and health; trace/heavy metal/toxics concentrations.

II. PROPOSED SOLUTIONS TO REDUCE GROUND-WATER LOSS, AND REDUCE DISCHARGES OF MODERATE VOLUMES OF REDUCED WATER QUALITY, FROM EIGHT (8) SECONDARY NSLWMD CANALS USED FOR AGRICULTURAL AND RESIDENTIAL DRAINAGE INTO THE NORTH FORK OF THE SAINT LUCIE RIVER, INVOLVE THE CONSTRUCTION OF WEIRS AND SMALL ATTENUATION FACILITIES (SAF) TO INCREASE THE LEVEL OF GROUNDWATER STORAGE TO REDUCE IMPACTS UPON THE FLORIDAN AQUIFER, AND TO INCREASE WATER RESIDENCE-TIME IN ORDER TO IMPROVE WATER QUALITY.

RESEARCH NEEDS

A. Model freshwater basins of the eight canals for weir design needs for groundwater recharge, drainage and location of Small Attenuation Facilities (SAF) which could add storage in the basins.

B. Examine the environmental impacts of weir/SAF construction at potential site locations for the eight canals.

C. Model the downstream impacts of freshwater, organic and toxics loads, and model load reduction provided by the weir/SAF system.

III. A PROPOSED SOLUTION TO FRESHWATER IMPACTS UPON THE INDIAN RIVER/SAINT LUCIE RIVER IS TO OPTIMIZE OCEANIC EXCHANGE THROUGH THE INLETS (IN ORDER TO REDUCE THE ANTICIPATED COSTS OF ESTUARINE RESTORATION AND PRODUCE A MORE RAPID RECOVERY OF THE ESTUARY).

RESEARCH NEEDS

A. Perform bathymetric studies of the Inlets and estuary to establish potential seagrass restoration sites.
B. Develop hydrological models of Inlet(s) exchange as it is related to freshwater discharge from canals, PAR/light transmissivity and seagrass abundance, restoration and health within the estuary.
C. Examine environmental impacts related to reduced sand transport by Inlets with "optimized" (vis-a-vis freshwater impacts) oceanic exchange, as well as, environmental impact studies of Inlet design improvements which result in reduced sand transport (and less beach renourishment).

IV. PROPOSED SOLUTIONS TO COASTAL IMPOUNDED WETLAND ISOLATION INCLUDE RESTORATION OF TIDAL EXCHANGE, SEASONAL MANAGEMENT AND ACQUISITION.

RESEARCH NEEDS

A. Perform studies on recruitment and habitat needs of marine fishes with wetland nursery requirements.
B. Perform studies on wading bird post-breeding requirements and the impacts of wetland management on juvenile success.
C. Perform studies on benthic organism habitat requirements, toxic substance uptake (and amplification) and reproductive success in coastal wetlands.
D. Perform studies on managed wetland enhancement of coastal and estuarine fisheries stock.
E. Perform studies on recruitment of juvenile fishes to estuaries and evaluation of such samplings as assessments of fishery populations.

V. IT HAS BEEN PROPOSED THAT THE BIODIVERSITY OF THE INDIAN RIVER LAGOON SYSTEM BE PROTECTED BECAUSE IT BEEN REPORTED THAT THE GREATEST LEVEL OF BIODIVERSITY FOR ANY ESTUARY IN THE CONTINENTAL UNITED STATES OCCURS IN THE INDIAN RIVER LAGOON.

RESEARCH NEEDS

A. Examine and develop comparative species records and species richness/diversity maps for locations within the Indian River Lagoon/Saint Lucie River system which are impacted and non-impacted by freshwater discharges.
B. Establish a monitoring program which evaluates the effectiveness of restoration efforts upon biodiversity, for coastal wetlands and estuarine waters at those specific impacted locations.
C. Provide suggestions for, and studies which contribute to, remediation plans for those areas deemed to have impacts upon biodiversity by freshwater discharges.
D. Evaluate the success of Pollution Load Reduction Goals vis-a-vis biodiversity.

March 18, 1994

Lawrence A. Burns, Ph.D.
Research Ecologist
U.S. Environmental Protection Agency
Environmental Research Laboratory
960 College State Road
Athens, Georgia 30605-2720

**Re: Central and Southern Florida Flood Control Project/
Congressionally-Authorized Restudy by the U.S. Army Corps of Engineers**

Dear Dr. Burns:

This is in response to your letter of March 2, 1994, requesting suggestions on research needs and issues analysis for the geographic area embraced by the project referenced above. This material will be presented to you in this hard copy format and on an IBM-compatible disk, WordPerfect 5 text.

As the Chief Engineer of the North St. Lucie River Water Control District (NSLRWCD) in St. Lucie County, Florida, I offer the following research needs and issues analysis, as we see them in our geographic area of interest and knowledge.

1. Discharge from Canals C-23, C-24, C-25 and C-44.

(a) It has been suggested by others that releases from these canal systems should be modified to decrease discharge during the wet season, and increase discharge during the dry season. However, these modifications, if any, must be made only after considering a balancing of needs for public water supply, agricultural water supply, drainage, and socio-economic benefits. A water budget must be prepared that realistically reflects these needs and their global impact on the environment and the economy.

Optimum discharges can be attained in part with the use of a regional attenuation facility (RAF) located within the area of influence of canals C-23, C-24 and C-25. This RAF could be used to store water in times of plenty, thereby reducing flows to the Indian River Lagoon during the wet season. During the dry season, it could be used to provide fresh water flows to the lagoon, as needed.

Accurate data, realistic research, and hydraulic and hydrologic modeling must be performed to determine these optimum flows.

(b) The 34-year operating history of C-23, C-24 and C-25 reveals that none is performing as originally designed in the 1950s. However, the original design information is still being used to estimate the reaction of those systems to rainfall events.

Therefore, actual flood profiles must be prepared for these three canals that accurately reflect their response to inflow and operating conditions. It is imperative that this data be prepared for the restudy to have any credibility.

2. Weir Structures in Secondary Canal Systems.

Weir structures in secondary canal systems discharging to the North Fork of the St. Lucie River, including those of the NSLRWCD, could assist in accomplishing more flexibility in the discharge of water from those systems.

Hydrologic studies to determine fresh water needs, groundwater recharge potential, and maintenance of historic drainage is required to determine where these structures should be installed.

Also, environmental impacts of the selected locations for these smaller attenuation facilities should be evaluated.

3. Modification of Fixed Crest Spillways.

Fixed crest spillways in C-23 (structure S-48) and in C-25 (structure S-50) could be modified to offer more flexibility in water storage and discharge capability.

Therefore, this option should be investigated and evaluated.

4. Groundwater Contour Maps.

It is important to understand the interaction between the surface water systems and the groundwater table in the areas impacted by St. Lucie County's major canal systems.

Therefore, recent and accurate groundwater table maps of the area should be prepared.

5. Data Collection Network for St. Lucie County.

A data collection network is needed to assess the reaction of St. Lucie County's surface water management system to rainfall, groundwater table conditions and stages. Without this basic data, it is not prudent to evaluate, or recommend modifications to, the existing systems.

Data needed includes stage and discharge for designated rainfall events, and water quality information.

These are just a few of the research needs and issues analysis that come to mind. As others may become evident at the meeting on March 22, I would like to call them to the attention of the participants.

Si[illegible]ely,

Richard B. Hellstrom, P.E.
Chief Engineer,
North St. Lucie River Water Control District

cc: Harold F. Brown

WRITTEN BRIEF

PALM BEACH COUNTY, FLORIDA ESTUARINE NATURAL RESOURCES INVENTORY AND RESOURCE ENHANCEMENT STUDY

MARCH 31, 1992

BY PALM BEACH COUNTY
DEPARTMENT OF ENVIRONMENTAL RESOURCES MANAGEMENT

The estuarine waters of Palm Beach County (PBC), Florida are contained within a shallow elongated lagoon 45 miles long with approximately 100 miles of shoreline. This study is part of an ongoing documentation of the county's estuarine natural resources. PBC Department of Environmental Resources Management (ERM) began its first inventory of intracoastal habitats in 1990 in the Lake Worth Lagoon Natural Resources Inventory and Resource Enhancement Study (Dames & Moore Inc., 1990). This second resource inventory includes the area north of Lake Worth Lagoon to Martin County, and the areas south of Lake Worth Lagoon to Broward County.

A primary objective of this study is to inventory impacted and natural areas for potential habitat restoration and enhancement. Field studies were conducted during the spring, summer, and fall of 1991 by ERM. The studies produced resource baseline information that is presented on maps. The maps include information on:

1. **Bathymetry:** The bathymetry map was created by digitizing the one-half and one meter contour lines found on the United States Geological Survey quadrangle maps. Spot depths and shoal areas throughout the study area were established by field measurements.

2. **Shoreline Characteristics:** The north and south portions of the shoreline in PBC were different in character with the south end of the county being considerably more developed. The shoreline at the north end of the survey (including canals) was 53% bulkheaded and 30% vegetated with mangroves. The shoreline at the south end of the survey was 89% bulkheaded and 7% vegetated with mangroves.

3. **Submerged Natural Resources:** The north end of the survey contained larger contiguous areas of seagrasses, principally in Jupiter Sound and the Loxahatchee River. These areas contained all of the *Syringodium filiforme* and *Thalassia testudinum* observed in this survey. In acreage, more *Halodule wrightii* was found in the north part of the survey than in the south, and more *Halophila* spp. was found in the south part of the survey. Almost all of the oyster beds were found in the Loxahatchee River. Corals and sponges were found only in the inlet areas.

4. **Manatee Habitat:** PBC estuarine waters provide year round habitat for manatees. Information gathered from over 1000 sightings of manatees was used to characterize manatee habitat within the estuarine waters of PBC. This map also includes the waters of Lake Worth Lagoon. The manatee habitat types designated are: 1) feeding areas, 2) resting/protected areas, 3) travelling areas, 4) freshwater attractant areas, and 5) warm water attractant areas. In many cases, areas were given more than one habitat type designation.

5. **Manatee Survey Location Data:** PBC, in cooperation with the Florida Department of Natural Resources (FDNR), began performing aerial censuses of manatees in PBC estuarine and marine waters twice per month in September, 1990. A total of 1128 manatees were sighted, of which 78 (9%) were determined to be calves. PBC estuarine waters were arbitrarily divided into 9 zones for analysis. The numbers of adult and juvenile manatees and their associated behavior are discussed for each of the nine zones.

6. **Marinas and Docks:** The facilities and dockage were characteristically different within the survey areas. In the northern area, 15 of the 23 facilities were commercial, in the southern area, 8 of the 43 facilities were commercial. Five boat ramps are in the northern area, and two boat ramps are in the southern area of the survey.

7. **Habitat Restoration and Enhancement Project Areas:** The ultimate goal resulting in the recommendations and proposed projects in the previous (Dames & Moore Inc., 1990) and current natural resources inventory is an increase in the habitat value and an increase in PBC's natural resources. A total of 64 potential project sites were identified, with 35 in the north and 29 in the south. An analysis of the ownership of the properties in the 64 potential project locations included 43 projects with publicly owned properties, and 32 projects with privately owned properties. PBC owned 10 properties, 8 in the north and 2 in the south. The County owns a total of 3.1 miles of shoreline considered in this survey for enhancement purposes, 2.9 miles in the north and 0.2 miles in the south.

RESEARCH NEED FOR HYDROLOGY MODELING FOR THE HABITAT ENHANCEMENT AND MANAGEMENT OF LAKE WORTH LAGOON

The West Palm Beach Canal (C-51) has had a profound impact on the Lake Worth Lagoon estuary as a major contributor of nutrients and sediments. Surveys have documented the accumulation of organically enriched silts in the vicinity of the C-51 Canal discharge.

The South Florida Water Management District's (SFWMD) redesign of the C-51 water basin, and the quality and quantity of discharges into the Lake Worth Lagoon are important in determining the long term viability of the estuary. How will this change affect the water quality, salinity, sedimentation, turbidity, and circulation of the Lake Worth estuary? To make competent management decisions, and enhance the Lake Worth Lagoon we need the expertise and resources of the SFWMD to design a hydrologic model of the lagoon for the specific purpose of enhancing and managing the estuary.

Science SubGroup Research Needs Assessment
Vero Beach Workshop Presentation
by Donna M. Smith
USDA Soil Conservation Service
21 March 1994

I am a hydrologist responsible for coordinating SCS's activities in support of the Indian River Lagoon National Estuary Program. In the way of an introduction, the following is offered and thought to be of significance to the proposed research topics. Among the activities that SCS initiated are an agricultural inventory, water quality research in citrus, and the establishment of two Mobile Irrigation Labs (MIL's) in the IRL basin.

In the C-25 basin there are 35,605 acres of citrus and 8,917 acres of range and pasture. The inventory showed that there are 38,793 acres being irrigated, with 32,657 acres of low volume, spray jet or drip (84% of the total irrigated) and 6,136 acres of crown flood.

Similarly, the C-24 basin has 20,870 acres of citrus, 120 acres of cropland (vegetables) and 43,556 acres of range and pasture. There are 20,870 acres being irrigated with 15,536 sprayjet (74%) and 5,334 flood. The C-23 basin has 22,596 acres of citrus and 13,602 acres of range and pasture. There are 22,596 acres irrigated with 17,015 sprayjet (75%) and 5,581 flood.

In FY 1993 and the first half of FY 1994 in the North St. Lucie River Water Control District we have evaluated [with the MIL's] 30 irrigation systems on 432 acres (all sprayjet) and made recommendations for increased emission uniformity for a potential water saving of 10,952.12 acre inches of water per year.

In addition to these project activities, normal field office operations include performing irrigation evaluations and water management plans similar to those being done by the MIL's. Another program is the water table observation well installation program, where water table observation wells are used to schedule irrigation. In Indian River County alone, 400 wells have been installed serving 15,000 acres and 72 cooperators.

For a discussion of research needs, under the headings:

Ecological Restoration Objective: **Remove muck from benthic areas of the IRL to reestablish seagrass beds and estuarine productivity.**

I thought that the Taylor study[1] had put this issue to rest, showing it to be cost-prohibitive, but regardless, this issue only makes me think of the source of the sediment. The source needs to be identified and stopped. Research data collected by SCS and others have shown that very little sediment is leaving mature citrus groves. If you've ever been in a citrus grove you know that they are grassed over and the farm ditches have water control structures when crown flood irrigation is used. My theory is that a lot of sediment comes from unpaved roads with the majority coming from canal banks during stormwater discharge. One research need is to identify the source of this sediment and quantify the amount from each source so that BMPs can be developed.

SCS designed and cost shared 2 radial gate structures on Ten Mile Canal in the 1950's under the authority of PL-566. These gates open from the bottom allowing suspended matter to continue downstream. These gates need to be retrofitted with gates with a split gate design. The cost of this project would be $123,000 for the smaller (Fittings Structure with three 4x7 foot gates and $190,000 for the larger (Gordy Road Structure with four 18x6 foot gates). There is also a need for a sediment control structure on Ten Mile between these two structures. Acquiring the funding for these retrofits would be a full time job for someone. I recently wrote a grant proposal for a Coastal Zone grant funded by NOAA and they didn't care for the project. We're waiting for the official turn down, but one

[1]Schropp, S.J., W.F. McFetridge, and R.B. Taylor. 1994. St. Lucie Estuary Muck Removal Demonstration Project: Final Report. Prepared for South Florida Water Management District, Contract C-3269. Taylor Engineering, Inc., Jacksonville, Florida. 116 pp. + Appendices.

of their big concerns was that we did not quantify the amount of reduction of sediments. We had given them the amount of deposition from the Taylor report [op. cit.] as 0.20 to 0.39 inches per year with an estimated 13,500 tons of sediment per year to the St. Lucie Estuary. This is another research need. Someone might also research where the money for the retrofit is coming from.

Hydrological Objective: Maximum freshwater discharges into the IRL through C-23, C-24, C-25 and C-44 should not exceed 2500 cfs.

I'm assuming that there was some research done to tie this into some ecological need[2]. How are we going to accomplish this? The agricultural community favors a regional approach rather than a grove by grove regulatory approach to reduce fresh water discharge. Most everyone can see that Regional Attenuation Facilities (RAF's) are the answer. Site location, land acquisition, permitting and site development will be time-consuming and expensive, but will be necessary to achieve 2500 cfs or anything close to it.

[2][Study reported by D. Haunert at Vero Beach workshop, March 22, 1994.]

ESTABLISHING LONG-TERM NET TRANSPORT PATTERNS IN ESTUARINE AND CONTINENTAL SHELF WATERS

Ned P. Smith
Harbor Branch Oceanographic Institution
5600 North U.S. Highway 1
Fort Pierce, Florida 34946

INTRODUCTION

An understanding of the movement of water in estuaries and over adjacent continental shelves serves as a least common denominator for a wide variety of ecological issues. By itself, volume transport defines circulation patterns associated with the movement of water through an estuary, the exchange of estuarine and shelf water though any connecting inlets, and the transport of water along and across the continental shelf. Studies of volume transport are rarely conducted alone, however. For most practical purposes the usefulness of transport studies rises dramatically when simultaneous measurements are made of what is contained within the water. When combined with any measure of dissolved or suspended material in the water, the result is directly applicable to pollutant transport, nutrient transport, larval transport and suspended sediment transport. When this broader approach is taken, transport studies are of fundamental importance whenever one wants to track the movement of dissolved or suspended material.

SCOPE

Within the geographical context of the coastal zone, one is usually concerned specifically with (a) estuarine transport, (b) continental shelf transport and (c) transport through the connecting inlets. Estuarine transport involves the mixing of fresh and salt water within the estuary itself. Continental shelf transport studies are divided generally into investigations of along-shelf and across-shelf transport. Across-shelf transport in particular is of central importance to the recruitment of larvae in those instances when adults spawn offshore and estuaries serve as juvenile nursery areas. Transport studies in inlets usually deal with the amount of water exchanged on a given tidal cycle, and on the long-term flood-dominant or ebb-dominant nature of the inlet.

In terms of the transport processes involved in coastal zone studies, the scope of a study must be broad enough to include (a) the ebb and flood of the tide, (b) the movement of fresh water through an estuary under both wet season and dry season conditions, (c) density-driven currents resulting from the juxtaposition of fresh water and salt water, and (d) the wind-driven movement of water arising with weather systems moving over the coastal zone or the seasonal shift in wind patterns.

In another sense, time scales of interest range from several hours (e.g., the ebb and flood of the tide) to several months (e.g., the changing patterns that arise in response to seasonal variations in wind and/or rainfall). The instantaneous ebb and flood of the tide may be the most apparent transport process at a given time and place, but the net movement over repeated tidal cycles may be relatively small. Longer time scales must be considered to determine the magnitudes and relative importance of all relevant processes.

RESEARCH NEEDS

(a) Estuarine transport

Transport processes in Indian River lagoon are undoubtedly better understood than are transport processes in shelf waters and in the connecting inlets. Nevertheless, the majority of measurements have been made in the relatively deep and protected waters of the Atlantic Intracoastal Waterway (AIW). While this has undoubtedly resulted in a higher data return, it has left open to question the role played by the relatively shallow waters on either side of the AIW in lagoonal transport patterns. Only recently have measurements been made to provide a better picture of the lateral structure of the flow patterns. To date, the variability has been documented, but no coherent picture has emerged. It appears that tidal ebbs and floods occur nearly simultaneously through a given cross-section.

Similarly, nontidal flow over time scales on the order of days to perhaps weeks occur simultaneously within and on either side of the AIW. Over the longest time scales, however, the flow in the AIW is not consistently related to the flow in the shallow waters. An understanding of long-term net transport patterns can be applied to the movement of fresh water through the lagoon, as well as to the transport of larvae from lagoonal or shelf spawning sites. Such an understanding will require more simultaneous in situ data combined with weather measurements, and perhaps supported by modeling studies if the cause-and-effect processes are not a direct response to local forcing.

(b) Continental shelf transport

As noted above, the two central issues within the context of continental shelf transport involve the movement of water along and across the shelf. Along-shelf transport is usually dominant, but the across-shelf deflection of a predominantly along-shelf flow is of importance in recruitment studies (where landward transport is needed to carry larvae toward inlets) and in pollution studies (where seaward transport is needed to carry water of low quality away from the coast and to open ocean waters where it can be diluted).

Along the Atlantic coast of Florida, the along-shelf transport over the outer shelf is dominated by the south-to-north flow associated with the Florida Current. The along-shelf flow over the middle and inner shelf is less well understood, but it appears that the long-term net flow is determined by wind conditions. South-to-north flow has been reported in spring, summer and early fall months; north-to-south flow has been recorded from late fall to early spring. Only one study has followed along-shelf transport over a full one-year cycle. Additional work is needed to determine interannual variability, or simply to document the similarity of flow patterns within a given season.

The across-shelf component of the flow has received considerably less attention. Several studies between Jupiter Inlet and Cape Canaveral have documented midsummer upwelling, but this is an indirect measure of across-shelf transport. The one-year study noted in the preceding paragraph revealed a near-bottom landward deflection of the northward flow in summer months, and a similar seaward deflection in winter months. Several questions remain, however. It is not clear if this is a result of the variable width of the shelf in the study area, or a result of an imbalance of forces in near-bottom layers. Also, it is not clear if the entire water column moves landward or seaward at a given time of year, or if the landward deflection in one part of the water column is compensated locally in another part of the water column at the same time. The vertical structure of the across-shelf flow is important when larvae migrate vertically over the course of a day and occupy both near-surface and near-bottom layers in the course of a migration cycle.

(c) Inlet transport

Least understood of all is the transport through the three inlets that serve Indian River lagoon. While the total tidal transport can be determined from an analysis of water level records obtained throughout the lagoon, it is not clear what fraction of the total is contributed by the individual inlets. Nor is it clear how much additional, nontidal transport is moving through the inlets. The long-period rise and fall of water level within the lagoon can be a response to either fresh water (some combination of rainfall and freshwater runoff moving into and through the lagoon from drainage canals) or salt water (nontidal exchanges through the inlets). The effect will be quite different, according to the source. Recent studies have suggested that the three inlets of Indian River lagoon are dissimilar in terms of their ebb-dominant or flood-dominant condition. Fort Pierce Inlet appears to be ebb-dominant throughout the year; St. Lucie Inlet is ebb-dominant at times, while at other times there appears to be little net nontidal flow. Sebastian Inlet appears to undergo a transformation from ebb-dominant to flood-dominant in response to seasonal variations in rainfall, wind direction, and coastal sea level. Studies are needed to confirm these preliminary findings, as well as to investigate relationships between long-term net inflow or outflow and spawning seasons of species that use the lagoon for a part of their life cycle.

APPROACH

As noted above, the approach taken to investigate physical processes in shelf and estuarine waters should combine direct field measurements with computer modeling. In situ measurements are needed to first initialize, then verify model simulations. Also, if a relatively small study area has been identified, direct measurements may be all that are needed to answer the questions being posed. On the other hand, many questions involve spatial scales large

enough to make direct observations prohibitively expensive. In such cases, computer models provide a more economical alternative. Also, once cause-and-effect relationships have been established, models provide an opportunity to explore a wider range of environmental conditions than might have existed while the field study was in progress.

SUMMARY

Regardless of the modeling or observational nature of the study, many questions will require an understanding of long-term flow patterns as a first step. Measurements of nutrients, larvae, suspended sediments, etc., can then be added to focus on the specific transport processes under consideration. In terms of volume transport, several studies are recommended to establish long-term net circulation patterns:

(1) an observational study conducted in shelf waters to determine across-shelf flow over the middle and inner shelf, and at both near-surface and near-bottom levels;

(2) a combination of observational and modeling studies conducted in lagoonal waters to compare and contrast transport within and on either side of the Intracoastal Waterway; and

(3) a modeling study designed to quantify the seasonal variability of long-term net transport through each of Indian River lagoon's three inlets.

REVIEW OF CENTRAL AND SOUTH FLORIDA FLOOD CONTROL PROJECT
UPPER EAST COAST PLANNING AREA
THE AGRICULTURAL PERSPECTIVE

by

Peter D. Spyke
President, Arapaho Citrus Management, Inc.

March 22, 1994

Vero Beach, Florida

INTRODUCTION:

I appreciate the opportunity of providing input on this important topic, and for the chance to be involved at this level of planning. This is a critically important step in the water management effort in this part of the state, and I commend the agencies involved for their foresight and responsible approach to changing perspectives and demands on the system.

Arapaho Citrus Management, Inc., is involved in the management and operation of businesses which produce citrus, sod, cattle, vegetables, and timber in Martin, St. Lucie, and Indian River Counties. Clients and members of our company also live and raise families in the urban areas of all of these counties. Therefore, as a group, we have a fairly complete perspective on the overall effects of the water and land management policies and regulations in this area. We actively participate on many of the boards and committees, including the Indian River Citrus League Land and Water Management Committee, the Treasure Coast Regional Planning Council, the Florida Cooperative Extension Service Advisory Committees, and the Indian River Soil and Water Conservation District, which deal with these issues and have been a part of the planning process for many years.

COMMENTS ON EXISTING PROJECT:

My personal perspective is perhaps unique. I was born in Broward General Hospital in Ft. Lauderdale in the summer of 1951. Four years before that, in the spring of 1947, my grandfather had purchased a small citrus grove with one-year-old trees, located on the south bank of the South New River Canal in Davie, Florida. That fall, the 1947 hurricane hit. An aluminum shed is still standing on that property which shows the water mark from the ensuing flood. The moderately acid water actually etched the aluminum, and one can plainly see the tiny increments of water level change as the water drained down from the Kissimmee, Lake Okeechobee, and the Everglades across the southeast Florida. Conservatively, at its highest the water was 5 feet deep in the grove, and it must have remained at a flood stage for weeks.

That year, my grandfather and father replanted the grove, and as a result of that and other storms, the Hoover administration authorized the Central and South Florida Flood Control Project. Forty-seven years later, there are hundreds of thousands of acres of agriculture and millions of people living on land that was not useable for any human-related purpose at that time. Therefore, it is clear to me that the Project was a tremendous success, and the chances are that the very people who are engaging in the discussion about the future would not even be here were it not for the assurances provided by the water control system developed as a result of the Project.

The Project, in my opinion, was inherently "good." Therefore, the exercise at hand is <u>not</u> one of fixing a "bad" thing, but how to make a "good" thing <u>better</u>! Part of this philosophy involves the realization that the <u>only</u> way to restore the system to its natural state would be for <u>everyone</u> to leave, take all of their belongings with them, and undo all of the changes they have made. Short of that, the ultimate solution will be a compromise which cannot make anything the same as what it was, but can be a sustainable situation which integrates the quality of human life with that of the natural environment.

PROJECT MODIFICATIONS:

Any modification will be a tradeoff between the human side and the environment. Nothing we do will result in a completely positive change for both sides of the issue. No improvement in the environment and natural

resources can occur without human effort, financial resources, and the loss of future options. Likewise, no change from the March 22, 1994, living conditions, population density, and land use can occur without some impact on the environment and natural resources.

The challenge is to define the target balance between the human issues and the environment and natural systems. A critically integral part of this process is to educate the public that every living human being, and all of their daily living habits, are part of the forces which have changed the environment and natural systems from the pristine condition. It logically follows that the responsibility for defining the target balance, enacting the changes, and accepting the outcome must be accepted by the entire group of humans which have influence on the area. Everyone is part of the problem, and everyone has to be part of the solution.

This approach eliminates the position that certain things are anyone's sole responsibility, or that someone else should fix something. Needless to say, the agricultural industry is the primary target of this kind of thinking. The land areas under agricultural production are greater than those in the urban areas, and therefore the amount of rain that falls on agricultural land is proportionately more. This is somewhat mitigated by the fact that the off-site impact of rain that falls on a citrus grove or even a vegetable field is usually less per unit area than the runoff from urban areas. The bottom line is that improvements are necessary on all fronts to stop further departure of the natural systems from their pre-development state, and to hopefully implement some reversal of the effects of human presence.

UPPER EAST COAST AREA STORMWATER ATTENUATION:

In light of this philosophical introduction, I'll get to the salient point. Everyone knows that the primary impact of the agricultural land development in the Upper East Coast Planning Area which was enabled by the Central and South Florida Flood Control Project is over-drainage of the St. Lucie Canal and C-23, 24 and 25 Drainage Basins. To a lesser extent, inter-basin transfer through the St. Lucie Canal has had some impact. However, the fundamental problem is that stormwater moves with a directed force which exceeds the natural sheet-flow drainage pattern.

Since the fundamental problem is simple, so is the theoretical solution: slow down the rate of discharge of stormwater. There are secondary issues such as low-flows, natural areas, wildlife corridors, and so forth, but the biggie is the drainage, and related water quality effects. Attenuation of fresh water discharges is necessary to reduce the effects of the fresh water itself, the velocity-related sediments and suspended materials, and various kinds of erosion. The best method would be to create stormwater retention reservoirs to temporarily detain freshwater discharges. Economic benefit could be gained if the reservoirs could supply irrigation water during dry periods, but sufficient justification from the reduction of detrimental environmental effects of the abnormal patterns of discharge is probable. A logical location at the southwest corners of the C-23 and C-24 for at least one of these areas has been identified. More of them would be better in the long run, but this one would have a profound beneficial effect.

This stormwater attenuation facility was identified as the Number One Priority at the recent Indian River Lagoon Consensus-Building Workshop. It received support from a wide range of interests at the meeting (at which I was the solitary representative from the agricultural industry). After the multi-disciplinary group examined almost every conceivable alternative for improving the Indian River Lagoon, this option emerged as having the most probable dramatic improvement.

Likewise, a study on agricultural discharge recently completed by the St. Johns River Water Management District in Indian River County showed that stormwater attenuation was the single most necessary change in the freshwater inflows to the Indian River. Contamination from other elements was fairly low, and the simple pattern of fresh water inflows was in and of itself the primary detrimental factor. Similar studies in the southern part of the Indian River Lagoon have shown the same thing. Therefore, the evidence pointing to this addition to the Project is overwhelming.

Likewise, a connection from the C-23 to Lake Okeechobee has been discussed at length. While it technically would allow inter-basin diversion, it could be regulated to reflect the pre-development state where some water from the C-23 did in fact drain to Lake Okeechobee under certain conditions. Without the connection, there

is no option other than to run all of the water from the C-23 drainage basin out through the St. Lucie River to tide. It's entirely possible, and feasible, to combine the attenuation reservoir with this connection to the Lake.

Both of these measures are structural in nature, which has lost favor in recent years. However, it would in fact be an adjustment to the original Project design which would afford environmental improvements. It would also convert existing uplands to wetlands, eliminate the possibility of a subsequent land-use change which would require more drainage capabilities, and connect the Upper East Coast to the Everglades system. The advantage of structural projects designed to afford environmental improvements has been demonstrated with great success in the Upper St. Johns River Project, so it is not a radical approach in any sense.

IMPLEMENTATION OF THE CHANGE:

Identification of the problem, while certainly difficult and incomplete, is the easy step. The tough part is figuring out a way to change the system, and the future, in light of the many divergent interests involved with the process. In our area, we all have come to realize and accept the existing weaknesses of the system. In agriculture, we have been instrumental in organizing the studies and discussions related to the solutions. South Florida Water Management District has provided willing cooperation, generously providing staff time, District resources, and financial support for efforts to learn more about alternative solutions designed to mitigate the detrimental effects of the Flood Control Project and the resultant land uses. The Indian River Citrus League and various agricultural groups have been partners in the discussion. I believe that, at this point, there are identified alternatives, but enacting them will involve many more people than just the agricultural industry.

In many ways, it's the same situation as is the case with the Everglades Restoration Plan. The general public instinctively believes that since agriculture is occupying the land, they should be responsible for restoration efforts. This ignores certain facts: agriculture's right to be there was implied when the Flood Control Project was conceived and constructed (which was long before most of the people who are criticizing the system became Floridians); that the realization or philosophy that we should preserve the environment occurred after agriculture was in place (up until that time, draining the land for human use was considered to be improving the environment); that there are legally-defined private rights associated with land ownership that transcend the public interest and vice versa; and that the Flood Control Project was a Public work, not one of agriculture *per se*. Therefore, the public is as responsible as anyone for changes or modification in direction of the Project.

There will be significant costs involved with changing the existing plumbing system. I believe that it is the responsibility of everyone to support the effort financially and in spirit. The stormwater reservoir and connection to the Lake would be useful additions to the Project which would benefit everyone in the basins, and would improve the long-term viability of the Indian River Lagoon. From that standpoint, it would be win-win. If the general public can be educated on the positive attributes of the changes and their responsibility to participate in the modifications, significant improvement could be made quickly. The outcome would be to permanently alleviate some of the negative environmental impact of the existing system. It is quite probable that if the changes are presented in this manner, the idea can become reality in the foreseeable future.

It must be remembered that the decisions related to environmental restoration have come about through the education and exposure of the general public, which includes agricultural operators, to the long-term effects of continued environmental degradation. The fact that anyone, farmer and homeowner alike, participated in the current state of loss of environmental function was due to a lack of knowledge of the results of our collective good intentions. Everybody has rights, opinions, responsibilities, and feelings relating to the matter, and any solution will ultimately involve us all. This philosophy should be considered in any discussion about the future of the Upper East Coast, the Everglades, or any other similar situation. Remember that the process has taken 50 years to reach the current state. The study, implementation, and financing of subsequent progress will be a similarly long-term exercise. There are no "right" answers--only those that appear to be intelligent, practical, and economically supportable. Let's work together toward that end, rather than engage in a finger-pointing exercise which is, after all, "pointless."

Again, thank you for the opportunity of participating in this meeting. I look forward to the future with the greatest of anticipation.

THE C-23 AND C-24 CANALS

A Report by Max Quackenbos
December 1993
Prepared for the
St. Lucie River Initiative, Inc.

Presented to the Science SubGroup
South Florida Ecosystem Restoration Federal Task Force
March 22, 1994
Vero Beach, Florida

By Max Quackenbos
Board Member, St. Lucie River Initiative, Inc.

Full copies of the original, including the Appendices,are available upon request from the
St. Lucie River Initiative, Inc., PO Box 2082, Stuart FL 34995
407/287-8158

SUMMARY

The C-23 and C-24 Canals were planned, designed and built by the U.S. Army Corps of Engineers under the authority of a Congressional Act of 1948. This federal initiative - the Central and Southern Florida Flood Control Project - authorized the Corps to undertake a vast alteration of the Florida landscape. Most of the work was in the low, flat plain south of Lake Okeechobee and extending to the east coast. The primary aim was flood control with water supply a second objective. Enhancement of fish, wildlife, and other environmental resources was mentioned but in the spirit and awareness of the past was not strongly supported.

The C-23 and C-24 Canals were constructed by the Corps under the same general authority, but also with specific approval of the 83rd Congress, 1954. They were planned to improve flood control in the inland areas of Martin and St. Lucie counties, and thus promote citrus and other farming, and cattle activities.

The canals had a local sponsor - the Central and Southern Florida Flood Control District, or CSFFCD. This state authority was created in 1949 by the Florida Legislature. For the two canals the CSFFCD agreed to:

1. Contribute 20% of the cost of construction.
2. Provide the right of way.
3. Assume all responsibility including costs of operation and maintenance for the canals, which were completed in about 1960.

The South Florida Water Management District (SFWMD) was created by the Legislature in 1972 to succeed CSFFCD, with broader responsibilities for flood control, water supply, and the environment in the sixteen southern counties of the state. Since 1972 SFWMD has owned, maintained, and operated the numerous canals and structures built by the Corps, with few exceptions.

The C-23 and C-24 canals are being recognized today as major polluters of the St. Lucie River. Together they discharge a vast amount of fresh water that upsets the salinity of the river. The discharge waters carry particles that settle as a foul ooze in the river bottom, or remain suspended as a gelatinous cloud, or a dark turbidity. These inputs intensified by those from the C-44, or St. Lucie Canal, bring devastating effects. The river has sadly declined as a haven for vegetation and animal forms. Some damage has been inflicted on the Indian River Lagoon.

Until recently the St. Lucie Canal was widely regarded as the heaviest polluter of the river - in dumping large amounts of excess fresh water from Lake Okeechobee mixed with runoffs of rural stormwater. That notion has now changed. With better management of Lake levels, the discharges have been reduced. The C-23 and C-24 are now the prime offenders - in 1992 and 1993 bringing 65% more water to the river than the St. Lucie Canal.

As the C-23 and C-24 Canals come into prominence it is evident that there is little local knowledge of their characteristics and operation. In this report we have tried to gather, analyze and condense the information scattered through several sources - mainly at South Florida Water Management District (SFWMD). So informed, local groups, and the St. Lucie River Initiative especially, will be better able to cooperate with the agencies that are now working to improve our river. They are SFWMD, the U.S. Army Corps of Engineers, and the Indian River Lagoon National Estuary Program (of the U.S. Environmental Protection Agency).

Omitting the descriptive matter that forms the bulk of this report (to be found in appendices A through F), we offer these conclusions about the C-23 and C-24:

- They operate efficiently to remove stormwater from farming areas in St. Lucie and Martin counties - a service essential to good farming.
- In the past two years, the annual amount so dumped into the St. Lucie River amounted to 350,000 acre-feet (for the Canals together).

As the canals have a small storage capacity the possible ways of reducing and diverting this water are at present:

1. On-site (farm) retention and better flow management - a partial solution with considerable reliance on 2. and/or 3.
2. Retention reservoirs - artificial and/or semi-natural
3. Transfer to Lake Okeechobee - after treatment (?). This alternative could provide extra fresh water now needed for Everglades National Park and Florida Bay.

These alternatives could include stormwater from C-44. The net total volumes involved will not be known until calculations are completed at SFWMD. These will show how much fresh water can help the North and South Forks of the St. Lucie River to maintain a beneficial salinity range, or envelope, that avoids extremes of freshness and saltiness.

ACKNOWLEDGEMENTS

The staff at SFWMD has been remarkably patient in answering questions and in providing directions to, or printouts from, good sources. Thanks for your gracious promptness.

Some of the discussion here is enriched by comments made during meetings of the Canalwater Pollution Committee of the St. Lucie River Initiative - Jim Dolan, Lee Jones, Pete Marovich, Gail Romero, Marty Sanders, Larry Schaffer.

We acknowledge, most gratefully, the secretarial help of Marianne Messersmith, Charles E. Geary, P.A.

LIST OF AVAILABLE APPENDICES

A. Design of canals and structures.
B. Operation and maintenance of canals.
C. Canal water.
D. Access to canals.
E. References.
F. Tables of information from SFWMD.

APPENDIX B

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

FY 1991-1995 PROJECT SUMMARIES

(The first two numerals of the project number indicate the fiscal year.)

PROJECT	FUNDING E-EPA M-MATCH	SPONSOR/CONTRACTOR	PROJECT DATES	PRODUCT/DELIVERABLE(S)
91-1 DIMS	E 49,467	SJRWMD #92W105/CSA	04/92 - 01/93	DIMS Report.
91-2 Program Inventory/ Base Program Analysis	E 48,976	SJRWMD #92W106/ECFRPC	01/92 - 09/92	Inventory & Analysis of Existing Gov. Reg. & Mgmt. Programs with FOLIO Data Base Suppl.
91-3 Impacts of Pruning Mangroves	E 15,000 M 45,000	SJRWMD #93W248/FDEP	10/93 - 09/95	Study to determine impact of pruning mangroves on productivity & habitat value. (See FY93 WP for complete project update.)
91-4 SAVI I--SAV Inventory & Analysis Phase I	E 48,058	SJRWMD #92W337	10/91 - 10/92	Development of SAV Initiative & focus of SAV as the "theme" for IRLNEP, SAV Mapping of entire lagoon, SAV Workshop.
91-5 Water Quality Monitor				Project orig. in FY91 WP as match; removed when Asst. Agree. was amended.
91-6 Toxic Substances Monitoring Network I	M 102,500	SJRWMD #90B180/FL Tech	10/91 - 06/93	"Toxic Substances Survey for the IRL System" submitted 2/93 on current status of trace metal contamination in sediments, water & biota.
91-7 Toxic Substances Monitoring Network II	E 40,000	SJRWMD #90B180 Amend 2/ FL Tech	10/91 - 09/93	This is the organic contaminants portion of the above contract.
91-8 Agricultural Runoff Inventory & Assessment		SJRWMD #92W196/NRCS	02/92 - 07/93	Originally budgeted at $45,000, NRCS completed project at no cost to NEP. Published report includes updated maps of agric. operations & an inventory of BMP effectiveness in protecting water quality.
91-9 Turkey Creek/Sebastian River Hydrodynamic & Salinity Model	M 77,967	SJRWMD #90B207/FL Tech	10/91 - 03/94	Network to collect meteorologic & hydrologic data for the model has been established; data collection is ongoing.
91-10 Water Quality & Circulation Modeling Review	E 36,784	SJRWMD #92W129/UF	05/92 - 06/93	Report, submitted in 4/93, reviewed modeling efforts in IRL & compared results of 1-D & 3-D models. 3-D models provide much more detailed info. on circulation & transport in the lagoon.
91-11 Reconnaissance Report Update	E 23,796	SJRWMD	07/92 - 09/93	An individual was hired to review & verify lagoon data & format datasets in SJRWMD data base. Products included a completed status & trends report & nutrient budget.
91-12 Coordinate ELCs	E 11,836	SJRWMD #93W137/ Volusia Co. DEM	02/92 - Ongoing	Regional Environmental Resources Directory has been distributed & Electronic Bulletin Board "Lagoon Net" is operating & continues to be refined.

PROJECT	FUNDING E-EPA M-MATCH	SPONSOR/CONTRACTOR	PROJECT DATES	PRODUCT/DELIVERABLE(S)
91-13 Citizens Monitoring	E 10,000	SJRWMD #92W246/ Marine Resources Council	10/92 - 10/93	Training guide has been completed & additional monitoring sites funded by NEP are collecting data.
91-14 Teachers Environmental Education	E 21,132	SJRWMD #92W280/ Univ. Central Florida	07/92 - 10/92	Two 10-day summer institutes were held for environmental educators involving "hands-on" instruction. Project was chosen by Congressman Jim Bacchus as one of four outstanding innovative educational projects in the region.
91-15 Neighborhood Action Plans	E 20,000	Print Media Associates Data Management	02/92 - 02/94	"Owners Guide to the Indian River Lagoon." Text, art work & printing were completed in 2/94.
91-16 General Public Outreach	E 20,012	SJRWMD	10/91 - 09/92	Two posters of the lagoon system, a synchronized sound/slide show, several newsletters about program activities, an exhibit display, & two storm drain stenciling events.
91-17 Watershed Action Committees	E 25,694 M 8,563	SJRWMD# 92W216, 92W217, 92W218, 92W219, 92W221, SFWMD# SJ93W174 & 79	10/91 - 05/93	Funding for six separate committees with seven demonstration projects.
92-1/CR-1P-CR-6P Characterization Report	E 275,000	SJRWMD #93W111/ Woodward-Clyde Consultants	02/93 - 09/94	Report with data assembly & review, physical features, biological resources, status & trends, & priority problems, along with historical imagery, uses of the lagoon, & governmental programs.
92-2P SAV Inventory & Analysis--Phase II	E 80,000	SJRWMD#93W216/FL Instit. Techn. SJRWMD#93W203/Brevard Co. SJRWMD #93W175/Indian River Co. SJRWMD #93W199/Harbor Branch Oceanog. Instit.	03/93 - 09/94 01/94 - 01/95 02/94 - 02/95 08/93 - 06/95	PAR monitoring data from Brevard & Indian River Co., intensive PAR monitoring data from Harbor Branch, reprinting of SAV workshop proceedings, & review & analysis of historic benthos samples.
92-3P DIMS Implementation	E 40,000	SJRWMD SFWMD	10/92 - 10/93	Funded continuation of a data manager to verify & format datasets for the lagoon. Data management review & status completed. GIS workshop held.
92-4P Fed. Asst. Programs Invent. & Consist. Analy.	E 10,000	SJRWMD #93W182/ECFRPC	04/93 - 08/93	Report that identifies goals & purposes of Federal Assistance programs in the IRL.
92-5P Lagoon Partners Fund	E 40,000	SJRWMD #93W175-176-181-183-186-208-284-285	10/92 - Ongoing	Provides "mini-grants" for demonstrations projects in the lagoon. Eight grants were issued FY92.

PROJECT	FUNDING E-EPA M-MATCH	SPONSOR/CONTRACTOR	PROJECT DATES	PRODUCT/DELIVERABLE(S)
92-6P Public Awareness Campaign	E 25,000 M 75,000	SJRWMD #93W139/ WMFE PBS Station	01/93 - 02/94	Speakers bureau video, ½-hour broadcast quality video, & three 30-second PSAs were produced.
92-7P General Public Outreach	E 7,200	SJRWMD	10/92 - 09/93	Funded promotional posters, facts sheets, etc.
92-8P Watershed Action Committee	E 28,000 M 6,666	SJRWMD SFWMD	08/93 - 10/94	Funded demonstration projects through the eight committees along the IRL.
92-9M Turkey Creek/Sebastian River Hydrodynamic Model	M 100,000	SJRWMD #90B207/FL Instit. Techn.	10/92 - 08/95	Continuation of Project 91-9 to develop 3-D model of IRL in the vicinity of Turkey Creek.
92-10M Photo interpretation & Digitization of SAV Coverage	M 20,000	SJRWMD #92W102/ Natural Systems Analysis	10/92 - 01/93	Review of aerial photo of SAV coverage from several years to help discern spatial & temporal trends.
92-11 Determination of an Ecologically Desirable Salinity Regime	M 50,000	SJRWMD #92W177/ Mote Marine Laboratory	10/92 - 12/92	Calculation of the most desirable salinity regime in the Sebastian River to assist in timed release of freshwater discharges.
92-12M Assessment of Agricultural Drainage	M 15,000	SJRWMD #92W130	11/92 - 03/93	Inventory & analysis of agric. activity lagoon-wide to determine annual & seasonal suspended matter loadings to primary canals in three of the lagoon's water control districts.
93-1/SAV-1P SAV Mapping	E 40,000 M 7,000	SJRWMD	10/93-12/94	SAV mapping throughout the lagoon
93-1/SAV-2P Lagoon Bathymetry	E 50,000	SJRWMD	10/93 - 12/95	Bathymetric survey & mapping of IRL to define areas of potential SAV coverage, etc.
93-1/SAVA-3P Light Availability Model	E 30,000	SJRWMD	10/93 - 09/98	Mathematical models to determine target levels for total suspended solids, color, & chlorophyll to control pollutants affecting light penetration.
93-1/SAV-4P Lagoon Segmentation	E 20,000 M 43,000	SJRWMD	10/93 - 09/98	Definition of homogeneous segments of IRL for analysis & management purposes.
93-1/SAV-5P Lagoon Monitoring	E 30,000 M 23,400	SJRWMD	Ongoing	Water quality & PAR data from throughout IRL for use in light availability modeling, etc.
93-1/SAV-6P Digitization of 1949 USGS Quads	E 31,700	SJRWMD	10/93 - 12/95	Digitization of 1949 USGS 7.5' quadrangles of IRL region & estimate of pollutant loadings by basin during that era.

PROJECT	FUNDING E-EPA M-MATCH	SPONSOR/CONTRACTOR	PROJECT DATES	PRODUCT/DELIVERABLE(S)
93-2/PIE-1P General Public Outreach	E 50,070	SJRWMD	10/93 - 01/96	Workshops, displays, education materials, etc.
93-2/PIE-2P Lagoon Partners Fund	E 50,000	SJRWMD #94W105-106-107-121-122-123-138-155-156-157-158	Ongoing	Continuation of 1992 Lagoon Partners Fund grant program. Eleven projects were funded in FY93.
93-2/PIE-3P Citizens Water Quality Monitoring	E 80,000	SJRWMD	Ongoing to 12/96	Support for citizens water quality monitoring programs through Volusia Co., Marine Resources Council, & Florida Advanced Technology Center (Brevard Labs).
93-2/PIE-4P Watershed Action Committee Projects	E 40,000 M 41,733	SJRWMD	Ongoing to 12/96	Support for demonstration projects for the eight committees in the IRL area. NEP & SWIM are coordinating to foster these projects.
93-3/CCMP-1	E 145,000	SJRWMD #94W118	04/94 - 11/95	Implementation & finance plan report development.
93-3/CCMP-2 Printing & Pub. of CCMP Material	M 150,000	SFWMD	10/93 - 12/95	Printing of documents to be included in the CCMP.
93-3/CCMP-3 Conferences & CCMP Hearings	E 25,000 M 20,000	SJRWMD #94W103 SFWMD	10/93 - 12/94	Three subregional assemblies (held in north, central & southern portions of IRL). Action plans are being developed to take to the regional action agenda assembly.
93-4/DI-1 Program Inventory & Analysis--Update & Maintenance	E 10,000	SJRWMD	Ongoing	Update of Government Programs Inventory & Analysis
93-4/DI-2 DIMS Implementation	E 10,000 M 42,500	SJRWMD SFWMD	Ongoing	Funded a permanent data manager & implementation of recommendations of DIMS report.
94-1/SAV-1 Bathymetry	E 80,000 M 40,000	SJRWMD/Contractor selected	10/94 - 12/95	Final phase of project initiated in 1992 for fine-scale bathymetric survey of IRL.
94-1/SAV-2 IRL Hydrodynamics & Water Quality Modeling	E 30,000 M 30,000	SJRWMD/UF	10/94 - 09/98	Second phase of project initiated in 1993 WP to develop a water quality model which identifies & forecasts parameters affecting light penetration in IRL.
94-1/SAV-3 Lagoon Monitoring	E 25,000 M 26,364	SJRWMD Counties	Ongoing	Continued support for lagoon-wide water quality & PAR monitoring network.
94-1/SAV-4 Optical Water Quality Model	M 10,000	SJRWMD	10/93 - 12/97	Optical water quality model & requirements for growth of SAV.
94-1/SAV-5 LU/LC & SAV Mapping	M 40,000	SJRWMD	10/93 - 03/96	Historical land use, agricultural & SAV mapping.

PROJECT	FUNDING E-EPA M-MATCH	SPONSOR/CONTRACTOR	PROJECT DATES	PRODUCT/DELIVERABLE(S)
94-1/SAV-6 Mapping SAV & Aerial Digitization	M 10,000	SJRWMD	10/93 - 03/96	Current SAV mapping & digitizing of aerial photos.
94-2/PIE-1 Lagoon Partners Fund	E 50,000	SJRWMD	Ongoing	Continued successful mini-grant demonstration/education program initiated in 1992 WP.
94-2/PIE-2 Citizens Monitoring	E 50,000 M 20,850	SJRWMD SFWMD	Ongoing	Continued funding to support network of citizens water quality monitoring.
94-2/PIE-3 General Public Outreach	E 50,000 M 2,486	SJRWMD SFWMD	Ongoing	Support for activities that promote education & awareness of objectives of NEP & CCMP development.
94-2/PIE-4 Local Government Assistance Projects	E 40,000 M 117,011	SJRWMD, SFWMD/ Counties, Local Gov'ts	10/93 - 3/96	Support for local government demonstration projects.
94-3/CCMP-1 CCMP Finance & Implementation Plan Development & Refinement	E 100,000	SJRWMD	Ongoing to 11/95	Continuation of development & refinement of implementation plan for CCMP.
94-3/CCMP-2 Printing & Production of CCMP Development Materials	E 60,000 M 30,000	SFWMD	Ongoing	Production & printing of CCMP, finance plan, & implementation plan, plus reprints of characterization report, etc.
94-3/CCMP-3 Conferences/CCMP Hearings	E 35,000 M 10,000	SJRWMD SFWMD	10/93 - 12/95	Workshops, public hearings, etc. to disseminate information on CCMP & to receive public comments.
94-3/CCMP-4 Program Inventory Update	E 20,000	SJRWMD	10/93 - 10/95	Update financial assistance program documents & compare goals & objectives of various assistance programs with those of CCMP.
94-4/DI-1 SAVI Demonstration Projects	E 40,000	SJRWMD	10/93 - 12/95	Demonstration projects to control factors affecting light penetration in IRL.
94-4/DI-2 Program Inventory & Analysis--Update & Maintenance	E 10,000	SJRWMD	10/93 - 12/95	Development of model standards & ordinances for local governments within IRL watershed.
94-4/DI-3 DIMS Implementation	E 20,000	SJRWMD	Ongoing	Support for operation of the DIMS for IRL.
94-4/DI-4 Regional Impoundment Mgmt Plan	E 10,000	SJRWMD	10/93 - 12/95	BMPs for lagoon marshes in context of ecological regions.
94-4/DI-5 CCMP Development	E 30,000	SJRWMD	10/93 - 10/95	Project to collect, disseminate info. for CCMP.

PROJECT	FUNDING E-EPA M-MATCH	SPONSOR/CONTRACTOR	PROJECT DATES	PRODUCT/DELIVERABLE(S)
95-1/SAV-1 Hydrodynamic/Salinity/ Light Attenuation/Water Quality Model Development	E 100,000 M 152,750	SJRWMD SFWMD	10/94 - 09/98	Data gathering for IRL water quality model to support Pollutant Loading Reduction Goals & to design & forecast effects of CCMP recommendations.
95-1/SAV-2 On-site Sewage Systems	E 60,000	EPA, SJRWMD	10/94 - 10/97	Assessment of nutrient loadings from On-Site Sewage Disposal Systems in priority areas defined by SWIM program.
95-1/SAV-3 Revision of Water Quality Monitoring Network	E 20,000 M 10,000	SJRWMD SFWMD	10/94 - 06/96	Revisions of IRL water quality monitoring network to reflect Pollutant Loading Reduction Goals & CCMP monitoring needs.
95-2/PIE-1 Citizen's Water Quality Monitoring Network	E 100,000	SJRWMD	Ongoing	Maintenance & expansion of water quality stations manned by citizen volunteers.
95-2/PIE-2 Public Outreach	E 40,000	SJRWMD	10/94 - 09/96	Production of brochures, fact sheets, & related materials to inform public about IRLNEP & CCMP recommendations.
95-2/PIE-3 Florida Yards & Neighborhoods	E 87,500 M 35,000	SJRWMD/IFAS, Counties	Ongoing	Support & implementation of Florida Yards & Neighborhoods Program to reduce non-point pollution from residences & commercial properties.
95-3/CCMP-1 Printing & Documents	E 60,000	SJRWMD	10/94 - 09/96	Printing & production of CCMP documents for public information.
95-3/CCMP-2 Conferences, Hearings, & Workshops	E 30,000	SJRWMD	10/94 - 09/96	Support for conferences, hearings, & workshops to discuss issues of importance to the Management Conference.
95-4/DI-1 Implementation of DIMS	E 75,000 M 35,000	SJRWMD SFWMD	Ongoing	Implement permanent archive for IRL data.
95-4/DI-2 Water Quality Monitoring Net	E 60,000 M 120,000	SJRWMD, SFWMD, Counties	Ongoing	Operation of IRL-wide water quality monitoring network.
95-4/DI-3 Grants Central	E 65,000 M 5,000	SJRWMD/St. Lucie Co.	Ongoing	Expand & refine environmental & community grants information network.

SUBREGION 4:

EVERGLADES AGRICULTURAL AREA

INTRODUCTION

The purposes of this chapter are to summarize important scientific work related to ecosystem restoration already accomplished and ongoing in the EAA (Figure 1) and to identify scientific priorities for the EAA. The discussion concentrates on the issues of soil subsidence and phosphorus as related to the EAA's major crops of sugarcane, sod, rice, and vegetables. Approaches that benefit the ecology and agriculture of the EAA are emphasized.

Soil subsidence is the major ecological issue in the EAA and the major obstacle for achieving a sustainable agriculture in the EAA. Several classes of organic, or muck, soils exist in the EAA. About 87% of these soils are composed largely of decomposed sawgrass (*Cladium jamaicense* Crantz) and may contain more than 85% organic matter. Soon after draining, scientists noted these organic soils were subsiding, or decreasing, in depth.

Soil subsidence is caused by physical, chemical, and microbiological processes. Although study is needed to further clarify its contribution to subsidence, oxidation of soil organic matter probably causes most of the subsidence now occurring in the EAA. This oxidation is caused primarily by microorganisms that thrive under aerobic conditions. As a result of the oxidation process, insoluble carbon portions of the organic matter convert to gaseous and water-soluble products. This conversion of carbon results in loss of soil mass.

Scientists have advised EAA growers since at least the 1940s that to increase the longevity of their agriculture, they must reduce the rate of subsidence. The most practical means of reducing subsidence is to maintain water tables as close to the soil surface as possible; the more soil within the profile that is inundated, the less oxidation occurs. Historically, this water-table management strategy has not professed to control subsidence completely with conventional agriculture of the EAA, only to reduce the rate of subsidence. Subsidence rates in the EAA have averaged about 3 cm (1.2 in) per year. However, due to changes in water-table management, the annual subsidence rate in the EAA now is probably less than 3 cm.

Scientists have experimented with alternate crops that could be grown under conditions that would completely control subsidence. Although they present a biological solution, these crops would not be practical because they do not have sufficient markets to warrant their commercial cultivation. Studies attempting to improve yields and expand markets of these crops should be encouraged.

Sugarcane (a complex hybrid of *Saccharum* spp.) is the predominant crop in the EAA. A successful sugarcane industry depends upon a large infrastructure. This infrastructure includes factories to convert sugarcane juice to raw and refined sugar; trucks, trains, railroad tracks, tractors, and wagons to transport sugarcane from fields to factories; and facilities to use sugarcane byproducts, such as to generate electricity for public utilities. South Florida faces severe economic consequences if ecological restoration means fragmenting EAA agriculture or changing it from a predominantly sugarcane agriculture.

Much of this chapter describes approaches in agricultural science and management that have the ultimate goal of no subsidence in the EAA. Improvements or changes in the hydrological system with changes in priorities for its management may be necessary to reach this goal. Past strategies to control subsidence proposed only partial control measures or use of crops not yet profitable. The objective of the scientific studies to control subsidence presented here is to completely control subsidence while cultivating sugarcane and other crops now grown profitably in the EAA.

Growers have already made important changes by including rice (*Oryza sativa* L.) in their sugarcane rotations, increasing use of summer floods, and growing all their crops at higher water tables. A scenario is

illustrated in this chapter that in the short term would reduce subsidence rates from a theoretical 3.66 cm (1.4 in) per year to 1.04 cm (0.4 in) per year. This major improvement could be achieved by summer flooding about 77,000 ha, 37% of the cropped EAA, and growing sugarcane with water tables at 30 cm (12 in) from the soil surface. Investigation is needed to identify sugarcane cultivars adapted to a 30-cm water table. Past research presents an optimistic outlook for quickly identifying such cultivars.

Further improvements would be more long-term and gradual, but previous research suggests that chances for success are good. The major needs for long-term investigation are to breed and select sugarcane cultivars adapted to water tables closer to the soil surface, determine stages of growth and height of water above ground at which flooding does not harm sugarcane, determine the duration of flood sugarcane can withstand without yield loss, and determine the proper management of alternate flooding and moderate draining that would not harm sugarcane while not permitting oxidation. Studies on rice should aim to extend flood duration by planting and harvesting it under flooded conditions. A standard condition of publicly supported genetic studies on all EAA crops should be to identify cultivars adapted to higher water tables and less phosphorus fertilizer.

Since the South Florida Ecosystem is massive and contains diverse regions, it is generally agreed that the restoration process must be holistic and adaptive. The approach identified here for the EAA meets both requirements. It is holistic because it would benefit both the EAA subregion and the ecosystem. It does so by proposing an agriculture that is managed to take advantage of natural weather patterns and hydrology. Doing so would help control subsidence and permit more water storage in the EAA. Potential benefits to the natural system would be the increased ability for water to flow south according to more natural hydroperiods and decreased need to release water in the east or west outlets from Lake Okeechobee. This approach is more adaptive than other solutions proposed for the EAA, such as publicly acquiring the EAA or constructing flowways within the EAA.

Phosphorus runoff from the EAA has received more attention than other EAA-related issues. Published reports and ongoing projects on phosphorus runoff show that much excellent work has been accomplished and major gains have been made. A workshop was held in April 1994 at which participants identified key concerns related to the phosphorus issue. The workshop summary (included in the discussion of phosphorus below) shows that the issue is complex and multidisciplinary. Further attempts at summarizing progress related to phosphorus should include teams of multidisciplinary scientists. The final section of this chapter summarizes opportunities for scientific cooperation to continue the South Florida Restoration process in the EAA.

BACKGROUND

"Even if the Army Engineers' project were a physical reality today, a thousand problems would remain to be solved. These will be problems in human relations, in the interplay of economic and political forces--all affected by what is done about water in the Everglades." (Fred C. Elliot, Chief Drainage Engineer of the Everglades from 1912 to 1931, in Bellamy 1948). Elliot's prediction has remained accurate. However, as we search for ways to sustain natural ecosystems and agriculture, and provide for urban needs, many of the most powerful solutions can be beneficial to many needs.

In 1949, the U.S. Government initiated the Central and Southern Florida Project for Flood Control and Other Purposes. The EAA evolved from this and other earlier drainage projects (Anderson and Howell 1993). This project intended to improve flood control and water supply, protect remaining wetlands, and reduce saltwater intrusion (Cooper 1989; SSG 1993). This project altered the natural ecosystem, but also tried to preserve natural sections of the ecosystem. Urban and agricultural influences on the ecosystem were expected to expand as a result of the project, but it was hoped the ecosystem would still sustain.

Gradually, as species became endangered, several invasive non-native species dominated natural portions of the South Florida landscape, and organic soils in the EAA subsided, it became clear that the ecosystem was no longer sustaining. Through the Interagency Task Force, the Federal Government is now evaluating processes to restore the South Florida Ecosystem and may use the South Florida Restoration initiative as a test case or a national model for ecosystem restoration (Brown 1994; Gifford 1994; Kenworthy 1994). This model must emphasize that sustainable ecosystems can contain sustainable agricultural systems and that improvements for agriculture or for the

natural ecosystem do not have to be at each other's expense. In so doing, we should follow the advice of Porter et al. (1991) and strive to make the EAA an international model of cooperation for concurrent environmental and agricultural progress.

The goal for the EAA presented in the Draft SWIM Plan for the Everglades (Whalen et al. 1992) is to "maintain a viable agricultural production area and ensure that adequate quality and quantity of water are discharged from the EAA to protect and improve the natural resources of the Everglades Protection Area," defined as WCAs 1, 2A, 2B, 3A, and 3B; ENP; and the Arthur R. Marshall Loxahatchee NWR. This chapter has a similar goal but emphasizes different subject areas. For a more complete picture of the EAA, understanding the approach of Whalen et al. (1992) is essential.

An important change in the goal of this chapter compared to that of the SWIM Plan is that "sustainable agriculture" replaces "viable agricultural production." Haberen (1994) stated what sustainable agriculture must accomplish: "Farming must be done in a way that guarantees a certain level of food supply for generations to come." Sustainable agriculture was defined by USDA (1994) as an "integrated system of plant and animal production practices having a site specific application that will, over the long term: 1) satisfy human food and fiber needs; 2) enhance environmental quality and the natural resource base upon which the agricultural economy depends; 3) make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; 4) sustain the economic viability of farm operations; and 5) enhance the quality of life for farmers and society as a whole." The term "sustainable agriculture" as used in this chapter refers to this USDA definition.

MAJOR ISSUES

The major EAA issues of soil subsidence and phosphorus are discussed below. These and other topics are also addressed in sections on EAA crops.

Soil Subsidence

The predominant soils of the EAA are Histosols or organic soils, comprising 313,639 ha (775,000 ac)(Cox et al. 1988). Of these, about 205,000 ha (506,555 ac) are used for agriculture (Anderson and Howell 1993). These soils range from 33% to more than 85% organic matter in the upper 21 cm (8.3 in) of their profiles (Zelazny and Carlisle 1974). A summary of these organic soils is presented in the support document of the Everglades SWIM Plan (SFWMD 1992b). More detailed descriptions are in Snyder (1987, 1994), Snyder et al. (1978), and Anderson (1989).

Due to their large amounts of organic matter, many agricultural practices routinely used on mineral soils are not successful on organic soils. These soils also pose challenging scientific issues related to sustainable agricultural and ecological systems.

Lucas (1982) described organic soil formation and Snyder (1994) described formation specifically for organic soils of the EAA. Immediately underneath EAA soils lie rocks of variable qualities. At places, the rocks form a hard limestone but more often a grayish-white calcareous mud. Generally, water does not move beneath this layer. For soils that formed from sawgrass, Miller (1918) reported seven weights of sawgrass were required to produce one weight of organic soil. McDowell et al. (1969) estimated soil formation from sawgrass began about 4,400 years ago. They estimated it took about 800 years to form the first 7.6 cm (3.0 in) of a marly muck on top of the bedrock and soils subsequently accreted at the rate of about 8.4 cm (3.3 in) per 100 years until they were drained.

Soil subsidence is the loss of depth of soil. In the organic soils of the EAA it is caused by physical, chemical, and microbiological processes. Physical factors causing subsidence include loss of buoyancy, compaction, and shrinkage due to drying. This is generally an initial phase of subsidence that occurs soon after draining. Although soil depth is lost due to these processes, soil is not lost. The microbiological cause of subsidence is

oxidation of organic matter. When flooded, the organic matter of EAA soils is protected from aerobic microbiological activity.

Once drained, the rate of microbial oxidation of the carbon reserves of the organic matter increases drastically. Cox et al. (1988) identified the responsible microorganisms as fungi, bacteria, and actinomycetes. This oxidation converts insoluble carbon portions of the organic matter to gaseous and water-soluble products, which results in loss of soil mass (Tate 1980b). Soil losses due to fire and wind and water erosion may also occur, although these have not been well quantified. The controlled burning of sugarcane prior to harvest does not cause subsidence because the fire generally does not spread to the soil.

Subsidence is the most important ecological concern in the EAA (SSG 1993). All other restoration matters related to the EAA must revolve around subsidence of its organic soils. To achieve a sustainable agriculture, subsidence rates must be reduced to lengthen agricultural life of the EAA and to help resolve complex issues facing the natural portions of the South Florida Ecosystem. Therefore, the goal of scientific study in the EAA related to achieving sustainable ecosystems should be to achieve a zero-subsidence agriculture.

Disagreement exists as to what extent subsidence in the EAA is due to oxidation. Neller (1944) determined oxidation and total soil loss were directly related. Stephens and Speir (1969) estimated oxidation may account for as little as 55% and as much as 75% of total subsidence in the EAA. Volk (1973) reported oxidation accounted for 58 to 73% of subsidence of organic soils in the EAA. Tate (1980) noted that 85% of subsidence for Histosols in the western Netherlands during the past 1000 years was due to oxidation. Future investigation should generate models specific to the various organic soils of the EAA that relate water table, temperature, and other important factors to percentage of ongoing subsidence due to oxidation. Losses not due to oxidation are probably due to erosion from wind and water and uncontrolled burning. Subsidence without soil loss may also occur due to compaction by heavy machinery. Subsidence due to these other causes needs to be quantified.

References to subsidence of EAA soils began at least as early as 1942 (Clayton et al.) and continued with Neller (1944); Mowry and Bennett (1948), and Allison (1956). Stephens and Johnson (1951) published predictions on rates of subsidence for EAA soils. Stephens and Speir (1969), Johnson (1974), Stephens et al. (1984), and Smith (1990) reported these 1951 predictions were on target. However, the predictions by Stephens and Johnson (1951) and Stephens and Speir (1969) that subsidence would end profitable agriculture in large areas of the EAA by 1990 and almost completely eliminate it from the EAA by 2000 were not correct. These predictions assumed that as soil depths ranged from 30 to 100 cm (12-39 in), agriculture would become uneconomical. However, resourceful growers in the EAA are already successfully farming soils with these shallow depths.

Cox et al. (1988) reported subsidence rates may be slowing. Possible causes for reduced subsidence rates are proportionately more soil remains inundated, a greater percentage of the remaining organic matter is more resistant to microbial decomposition, and a greater percentage of the soil becomes mineral rather than organic as subsidence continues. From the same data source, Stephens and Johnson (1951) and Shih et al. (1977a,b, 1979) reported subsidence rates in sugarcane were 70-75% of those found in pasture or vegetable crops when all three crops were held at similar water tables. Two factors suggested as causes of this decrease in subsidence are toxins released by sugarcane roots and lower soil temperatures with sugarcane compared to other crops. The steady growth in Florida sugarcane area since 1966 when Hebert (1967) reported 76,950 ha (190,143 ac) to the latest estimate of 179,480 ha (443,495 ac) (Glaz 1994) may have helped slow subsidence rates. About 155,000 ha (383,000 ac) of sugarcane are in the EAA (Glaz 1994).

Snyder et al. (1978) estimated an organic soil that began with a 3.04-m (10-ft) depth would eventually subside to about 7.6-10.2 cm (3-4 in) of mineral matter above bedrock if subsidence continued without control. This is clearly not desirable for agriculture or the ecosystem, which under its natural state accreted muck soils slowly.

Subsidence does not occur at uniform rates on all organic soils of the EAA. Snyder et al. (1978), McCollum et al. (1978), and Cox et al. (1988) reported seven categories of muck soils in the EAA. The Torry muck series, comprising about 7% of EAA muck soils, has a mineral content of 30-70%. Due to this relatively high mineral content, its rate of subsidence is lower than that of other organic soils in the EAA. Terra Ceia, Pahokee, Lauderhill, and Dania mucks comprised 86.8% of the EAA in 1988. These are the soils composed largely of

decomposed sawgrass; they have similar chemical properties and often contain more than 85% organic matter. The principal distinguishing characteristic among these four soils is depth to bedrock; Terra Ceia is the deepest and Dania is the most shallow. As subsidence progresses, a Terra Ceia gradually becomes a Dania muck. By reversing subsidence, or accreting soil, a Dania muck would become a Terra Ceia muck. Okeechobee mucks (2.6% of the EAA) have an underlaying horizon of peat[1] under the surface layer of muck. Okeelanta mucks (3.6% of the EAA) have a 40- to 101-cm (15.7- to 39.8-in) horizon of muck on top of a fairly extensive horizon of sand. Snyder (1994) presents a comprehensive summary chapter of these soils.

The latest estimates of the percentages of Terra Ceia, Pahokee, Lauderhill, and Dania mucks were developed using ground-penetrating radar (Collins et al. 1986; Cox et al. 1988). The most important monitoring program needed for the EAA is one to monitor subsidence. Current soil depths must be determined and a monitoring program must be set up that will annually measure soil depths. As we strive to develop farming systems with lower rates of soil loss, this monitoring would indicate the degree of success of such systems.

Stephens et al. (1984) presented equations for estimating rates of subsidence. One equation related rate of soil subsidence to average water-table depth; another linked the combined effects of soil temperature and water-table depth on subsidence. Browder and Volk (1978) designed a systems model to test different management practices for slowing the rate of subsidence. Several studies on soils in the EAA have described oxidation processes at the microbiological level (Duxbury and Tate 1981; Tate 1976, 1979a,b, 1980a,b; Terry 1980; Terry and Tate 1980). All these studies have provided the general knowledge that rates of subsidence are less with cooler temperatures and higher water tables.

There has not been sufficient agronomic work to test these general principles to reduce subsidence rates, although Stephens and Johnson (1951) emphasized the need for such work. Jones (1948) advised "Strict regulation of the water table is desirable on cultivated areas of Everglades peat--that is, the water table should be low enough during the growing season to permit the crop to develop but high enough to prevent avoidable oxidation and subsidence of the peat."

Almost all EAA studies that have measured subsidence have determined it occurs at the rate of 2.5-3 cm (1-1.2 in) per year. The equation of Stephens et al. (1984), $Y = 0.0643X - 0.259$, shows how subsidence, Y (cm), changes due to depth of water table from the soil surface, X (cm). If $Y = 3$ cm, then X = water table for the past 50 years = 50.7 cm. This indicates our knowledge of the effect of water-table depth on subsidence is incomplete because the EAA water table has probably averaged more than 51 cm (20 in) from the soil surface during the past 50 years.

Measurements of Andreis (1976) differ from predictions of Stephens et al. (1984). Andreis measured subsidence for 4 years, in fields growing sugarcane with average water-table depths of 48 and 94 cm (19 and 37 in). These fields had been cultivated for only 3 years prior to this experiment. He reported annual rates of subsidence due to oxidation of 3 cm (1.2 in) at the 94-cm depth and 0.8 cm (0.3 in) at the 48-cm depth. The formula of Stephens et al. would yield a subsidence rate about 3.75 times more than that measured by Andreis.

Some indirect evidence and a small number of direct water-table measurements exist for the EAA. Gill et al. (1979) identified a high water table as 30 cm and water tables in commercial sugarcane fields ranging from 90-120 cm (35-47 in) from the soil surface. Andreis (1976) described 50.8 cm (20 in) as a high water table and 91.4 cm (36 in) as a low water table. Kang et al. (1986) identified a normal sugarcane water table as 56.2 cm (22.1 in) and a high water table as 29.8 cm (11.7 in). CH2M Hill (1978) measured the water table in one sugarcane field for 15 months and reported an average depth of 63.5 cm (25 in) from the soil surface. In 1981-1983, water-table measurements were taken at three locations, two Lauderhill mucks and one Terra Ceia muck. During this 3-year period, the average depth was 57.1 cm (22.5 in) (Glaz, unpublished data, 1983). Izuno et al. (1991a) reported an average 21-month water-table depth of 62 cm (24.4 in) in one field. Coale et al. (1994a) reported an average water-table depth of 60 cm (24 in) in a 2-year study.

---

[1]Peat and muck are sometimes used interchangeably. Here, they refer to stage of vegetative decomposition, a muck being more decomposed than a peat.

This limited evidence suggests that since 1976 average water tables in commercial sugarcane fields have ranged from at least 56 cm (22 in) to more than 91 cm (35.8 in). At these water tables, according to the Stephens et al. (1984) equation, subsidence would have occurred at rates of 3.34-5.59 cm (1.3-2.2 in) per year. These rates are higher than measured rates. A science priority is to predict subsidence rates at various water-table depths for the seven classes of organic soils in the EAA. Casual observation would suggest that growers in the EAA have maintained water tables closer to the soil surface during the past 2 years than they have in previous years.

Agronomic science to control subsidence

This section proposes science and management strategies for maintaining a profitable agriculture and controlling subsidence in the EAA. Simply because management strategies are mentioned does not mean that private companies in the EAA will be able to implement them immediately. A general management strategy over large land areas takes time to implement, and unforeseen obstacles often impede progress. Undoubtedly, growers and scientists will need interdisciplinary approaches to overcome hydrological and other issues resulting from implementation of proposed strategies. A research strategy is just that, a research strategy. If scientists already knew the answers to problems, there would be no need for research. Therefore, farmers will not adopt new practices simply because they are being researched.

Successful farming involves more than correct applications of biological and hydrological principles. It also depends on prices farmers obtain for their products. Over long terms, we cannot predict or even approximate many of the prices and markets of many potential agricultural products biologically capable of growing in a sustained manner in the EAA. However, we are always faced with limited resources for science. Therefore, we must choose which crops hold the most potential for being part of a sustainable agriculture in the EAA. Investigations should concentrate primarily on these crops. Nonetheless, we should not rule out other crops. Many uncontrollable events that affect markets can occur. Therefore efforts on promising alternate crops should be maintained at moderate levels.

There are perhaps three reasons why pursuing a zero-subsidence agriculture in the EAA, equally profitable to the current practice, has received insufficient attention:

- First, there is the perception that a zero-subsidence agriculture must involve continuous flooding.

- Second, since the endeavor is perceived as a long-term, high-risk project, those concerned about natural portions of the ecosystem tend to prefer seemingly quicker remedies that usually involve fragmenting agriculture in the EAA.

- Third, many contend that hydrologically we cannot meet this goal. Some argue there is not sufficient water; others contend that pumping capability is not sufficient to prevent damaging agricultural floods.

Previous scientific investigation neither categorically refutes nor supports these general opinions, which are discussed in more detail below. The science program for the EAA must concentrate on answering these important questions:

1. Is continuous flooding necessary to control subsidence?

There is a strong case that continuous flooding is not necessary to control subsidence. Predrained EAA conditions cannot be exactly determined, but evidence suggests continuous flooding did not occur in the EAA as soils accreted. Botanists suggest the sawgrass plain that once dominated the EAA landscape may not have occurred under continuous flooding. Zaffke (1993) reported that sawgrass tolerated ranges of inundation from 15-94%. Lowe (1983) reported peaks of maximum biomass production in the Upper St. Johns River basin occurred at 80-85% and 73% inundation. He also cited Sincock (1958), who noted that most sawgrass in the Upper St. Johns occurred under frequency of inundation of about 45%.

With the shallower organic soils today, the Natural System Model (Fennema et al. 1994) predicts the EAA would remain flooded from 300 to 360 days of a normal year in the absence of man-made structures. Since soils were up to 1.5 m (4.9 ft) deeper in the natural system, perhaps they were flooded for shorter durations.

Snyder (pers. comm.) supports the theory that continuous flooding will not be necessary to control subsidence. He maintained a field in rice for 8-10 months per year for 10 years. Measured soil loss for this 10-year period was less than 0.2 cm (0.08 in) per year. This information must be used carefully. It was not collected under replicated conditions, and the experiment was not repeated across locations. However, since adjacent fields subsided at rates about 15 times higher than this rice field, the flooded rice probably reduced subsidence rates substantially. The extrapolated equation of Stephens et al. (1984) predicts that a constant water table of 4 cm (1.6 in) below the soil surface would result in zero subsidence. Brooks and Lowe (1984) theoretically predicted that saturation 60% of the time would control subsidence of organic soils of the Upper St. Johns basin.

Summarizing our insufficient scientific knowledge of oxidation of organic soils in the EAA permits the reasonable hypothesis that less than a continuous flood is necessary to control subsidence due to oxidation. Oxidation is caused by microbial activity mostly under aerobic conditions, and its rate increases as soil temperature increases. Questions that science needs to answer are:

- How long a summer flood is necessary to eliminate subsidence due to oxidation? Microorganisms that cause oxidation are aerobic and temperature dependent. Relative microbial activities in summer and winter should be determined.

- Subsequent to a flood, will these microorganisms decompose recently incorporated plant material before oxidizing the more decomposed muck soils? If so, does plowing under the nonharvested portions of a crop help control subsidence, and will doing so allow a longer period that the soil does not have to be flooded?

- If only a summer flood is insufficient to control subsidence caused by oxidation, how many floods during autumn, winter, and spring, and of what durations, will control it?

Science also must determine the effects of fluctuating water tables on oxidation rates. Porter et al. (1991) stated that wetting and drying cycles increase oxidation compared to maintaining a constant water level. Broadbent (1960) and Sorenson (1974) reported increases in microbiological activity due to wetting and drying soils. However, Tate (1979b) did not find that wetting and drying increased oxidation. Stephens and Johnson (1951) reported subsidence was lower in a "variable" 82-cm (32-in) water table than in a constant 82-cm water table. In the variable water table, the water was raised to 15 cm (6 in) once per week and then dropped quickly to 82 cm. These conflicting results suggest wetting and drying can reduce or increase oxidation rates. Proper management of wetting and drying cycles would probably produce desired results.

2. Can short-term approaches help control subsidence?

Some contend that developing zero-subsidence agricultural systems in the EAA would be too long-term and high-risk. Two reasonably safe assumptions suggest that substantial short-term, low-risk improvements in subsidence, compared to the historical rate of 3 cm per year, are attainable. The first assumption is that a lengthy summer flood will substantially reduce the rate of subsidence compared to land that is not flooded. The second assumption is that some of Florida's current commercial sugarcane cultivars would do as well under 30-cm water tables as under current 60-cm water tables. The combination of expected short- and long-term gains lends itself well to the adaptive process for restoration, because changes would occur gradually. Additional discussions of long- and short-term approaches appear in sections on rice and sugarcane.

3. Is the EAA hydrologically capable of controlling subsidence?

The third reason for not pursuing a zero-subsidence agriculture is that, hydrologically, the EAA may not be capable. Hydrological issues in South Florida pose a special challenge to agriculture and restoration. The logic behind the agricultural systems proposed here is that they adapt to water conditions closer to those that would occur naturally in the EAA today. The issue is more complex, however, because even without agriculture, the EAA of

today is expected to contribute to the water needs of the urban and natural sectors. In addition, agricultural crops cannot always be left to natural water conditions. When water levels stay too high or too low for too long, major economic losses may occur.

One would assume that after urban and other man-related water needs are met, flooded conditions could still exist in much of the EAA in most summers. Growers, however, could not depend upon, and often would not want, consistently flooded conditions in winters. Enough water may not be available to flood the entire EAA every summer, and this is one important reason rice production must remain limited to only a portion of the area (see below). Having a crop with more flexible water requirements, like sugarcane, does not put growers at risk of economic hardship in dry summers when they cannot flood all their land due to competing needs of natural and urban sectors of the ecosystem.

A thorough hydrologic analysis is needed for several issues. A comprehensive study using long-term weather patterns and proposed EAA water needs should determine how often the EAA might have too much or too little water for proposed agricultural systems.

A typical field in the EAA is 14-16 ha (35-40 ac), 804 m long x 196 m wide (2638 x 643 ft). At the front and back of each field (across the 804-m length) is a canal, often about 5 m (16.4 ft) wide. At each side is a field ditch usually 2-3 m (6.6-9.8 ft) wide. This configuration allows growers to manage water table levels and move water among fields. With these ditch spacings, growers expect there will not be a substantial gradient in water table from the field ditches to the center of the field. However, disagreement exists as to what gradient exists under different conditions. This should be determined. These canals are usually connected to a primary or secondary SFWMD canal. Therefore, growers can move water from most of their fields back to District canals, and they can receive water from District canals.

Scientists must determine what improvements this combined public and private water management system will require in order to move water among fields when irrigation or drainage is urgently needed by growers. These needs would be more precise and often more urgent under the proposed agricultural system compared to the current system. Rahi and Shih (1979) performed part of this investigation by studying soil-water characteristics. Also, scientists should try to determine what modifications in current water-control facilities would enable the proposed agricultural system to deliver more and better quality water at more appropriate times to natural portions of the ecosystem. This would help tie the proposed EAA agricultural system to the holistic ecosystem restoration approach.

Conservation tillage

Soil subsidence in the EAA is due primarily to oxidation caused by aerobic microorganisms. Science to control soil subsidence should concentrate on understanding and controlling soil oxidation. Other factors, however, are also partially responsible for soil subsidence. Studies to evaluate their relative importance to the subsidence process will help determine how much effort should subsequently be directed at these factors.

One such factor is loss of soil through wind erosion. Quantifying this may be complex because soil that blows off one field in the EAA may simply land on another field. However, soil may also be blown out of the EAA or into canals where it may flow out of the EAA. One tool used to control soil erosion due to wind is conservation tillage. Conservation tillage needs to be studied in the EAA not only because of its potential to reduce wind erosion, but also to determine if it could reduce oxidation rates. Previous studies already cited have not shown any differences in rates of subsidence in the EAA due to land preparation or cropping system, with the exception of Stephens and Johnson (1951) and Shih et al. (1977a,b, 1979). Both studies reported subsidence in sugarcane fields was only about 70% as fast as with other cropping systems.

In a review article that did not concentrate on the EAA, Reicosky et al. (1995) showed conservation tillage generally helped conserve soil organic matter compared to conventional tillage practices. They state that one reason for improved conservation of organic matter with conservation tillage is that the rate of biological oxidation is reduced. Hunt (pers. comm.) states that conservation tillage reduces water and wind erosion, reduces rate of soil organic matter decomposition, and generally lowers soil oxygen levels.

Conservation tillage techniques are already being looked at in the EAA as BMPs to reduce phosphorus runoff. Study of conservation tillage should be expanded to determine its effects on soil subsidence. In addition, use of advanced conservation tillage techniques could help EAA farmers overcome some of the logistical problems of using heavy equipment in waterlogged fields if they pursue use of a zero-subsidence agriculture.

Rice and Short-Term Solutions to Subsidence

The Everglades Research and Education Center of the University of Florida's Institute of Food and Agricultural Sciences has completed studies that have helped establish rice as a summer crop in the EAA. These investigated nutritional (Anderson et al. 1987; Deren et al. 1992; Elliot et al. 1988; Elliot and Snyder 1986; Snyder et al. 1986b; Snyder and Jones 1988a,b); entomological (Cherry et al. 1986; Foster et al. 1989; Jones and Cherry 1986); pathological (Datnoff, Snyder, and Deren 1992); agronomic (Jones 1993; Jones and Snyder 1987); economic (Alvarez et al. 1989); and water use (Shih et al. 1982, 1983) issues. The latest census indicated the 10-year average rice hectarage in Florida was 5,030 ha (12,429 ac) (Coale et al. 1992). The 1991-1993 average rose to 8,815 ha (21,782 ac).

Most rice in the EAA is grown in rotation with sugarcane; some is rotated with winter vegetables. There is an immediate need to compare subsidence rates of sugarcane-rice rotation with continuous sugarcane. These studies should also analyze subsidence with vegetable-rice rotation. A concentrated science, education, and extension initiative aimed at further increasing rice planting in the EAA should begin immediately. The initial rationale for growing rice should be that growers would benefit economically by its use, regardless of subsidence. After more precisely quantifying Snyder's (pers. comm.) conclusion that a summer rice crop will substantially control subsidence, then the additional economic benefit of controlling subsidence could be included among reasons to use a sugarcane-rice, vegetable-rice, or sugarcane- or vegetable-summer flood rotation.

Expected reduction in subsidence is not the only reason flooded rice is a logical summer crop in the EAA. In addition, rice needs water when water is abundant in the EAA, during the summer. An agricultural crop that would need to be flooded during the drier winter months probably would not succeed in the EAA due to competition for water with urban and natural needs. Any species that does poorly under hot, humid, high water-table conditions in the summer should not be considered. Likewise, any species that cannot withstand the cooler and drier weather of winter should not be part of the plan. This approach also agrees with a rain-driven restoration strategy.

One argument for not expanding rice production in the EAA is that sufficient water would not be available. Shih et al. (1982) showed that overall, and in most individual months during which rice growth is recommended, ET of rice is less than monthly rainfall in the EAA. Jones et al. (1994) presented a table of these data. Since the EAA receives water from sources other than rainfall, water availability should not often be a problem. However, droughts may jeopardize rice production in the EAA in some years. Drained conditions for short periods may not harm rice yields, depending on the stage of rice growth when drought occurs. However, long periods of no flooding would lower rice yields. To compensate for changes in agriculture that will help enhance the ecosystem, the restoration process must devise hydrological systems capable of maintaining flooded conditions for rice during at least moderate summer droughts. These hydrological safeguards would also promote the ecological benefit of controlling subsidence.

Jones et al. (1994) discussed other positive environmental effects of rice: 1) less nitrogen would be released by mineralization; and 2) like sugarcane, rice requires low fertilizer levels and produces well with residual nutrients of previous crops. Thus rice, like sugarcane, could act as a buffer to reduce nutrient runoff from the EAA and thereby help maintain the current level of winter vegetable production.

Rice can have a substantial positive impact as the EAA evolves to an agriculture that contributes positively to the ecosystem. However, rice should not be regarded as a panacea for the EAA. As discussed later, hydrologically, a monoculture of rice in the EAA may pose problems. Biologically, rice is almost entirely planted in rotation with sugarcane in the EAA. This means that a field is not planted with rice more than once every 4 years. Datnoff (pers. comm.) cautioned that the major reason rice sheath blight has not become a serious disease in Florida is that rice is not grown continuously on the same land. Also, rice can be grown without added fertilizers because it uses residual fertility of other crops. Rice would lose this advantage if grown in monoculture.

A critical topic for scientific study is rice harvest technology. About 50% of EAA growers harvest rice twice from the same planting. They harvest initially 115-135 days after planting; 75-85 days later they harvest a ratoon crop. The fields are drained before each harvest. Often due to excessive rainfall and to meet harvest schedules, fields are drained rapidly and left drained for about 14 days. Temporarily draining rice fields may reduce the benefits of flooding on reducing soil subsidence, although this needs to be verified and quantified. Draining may also increase phosphorus export from farm fields to canals. Studies like those of Izuno (pers. comm.) of water management systems that allow draining water from some fields onto others should continue. Another approach that would favor both phosphorus and subsidence issues is to develop rice harvesting equipment that would allow growers to harvest rice while it remains flooded.

Growers in the EAA typically plant rice on drained fields and wait at least 3 weeks, until the rice plant is tall enough, before flooding. Water control must be precise when the rice is first flooded because if water covers these young rice plants, they will die. In other rice growing regions, rice seed is applied by air to flooded fields. The seeds germinate and young rice plants survive even though they are submerged. Since this would allow at least 3 extra weeks of flooding, investigations to make this practice feasible in the EAA are needed. Perhaps before such studies are initiated, effects of the extra weeks of flood on controlling subsidence should first be determined.

Short-term increases in rice hectarage in the EAA should be achievable without major changes to sugarcane or vegetable systems or losses in farm profitability. In 1993, sugarcane occupied 179,480 ha in Florida and about 155,000 ha in the EAA (Glaz 1994). Sugarcane is typically planted and harvested annually three times. The first harvest is called the plant-cane harvest and the last two harvests are called ratoon harvests. Sugarcane growers in Florida plant sugarcane under successive and fallow planting systems. In the successive system, growers plow out and replant their fields immediately after the last-ratoon sugarcane harvest. In the fallow system, growers wait almost one year until the following sugarcane planting season to replant their fields with sugarcane. During the 1991-93 seasons, growers planted 31.5% of their sugarcane under the fallow system and 68.5% under the successive system (Glaz 1994). Fields planted in the fallow system can be cropped to something other than sugarcane one out of every four summers (Table 4). Rice has become an increasingly popular use of this fallow land.

Table 4. Fallow and successive sugarcane planting systems.

Year	System	Activity
1 Summer	Fallow	Land idle or planted to alternate crop
1 Fall	Fallow	Plant sugarcane
2	Fallow	First sugarcane harvest (plant cane)
3	Fallow	Second sugarcane harvest (first ratoon)
4	Fallow	Third sugarcane harvest (second ratoon)
5 Summer	Fallow	Land idle or planted to alternate crop
1	Successive	Harvest sugarcane, plow out stubble and plant sugarcane
2	Successive	First sugarcane harvest (plant cane)
3	Successive	Second sugarcane harvest (first ratoon)
4	Successive	Third sugarcane harvest (second ratoon)
5	Successive	Harvest sugarcane, plow out stubble and plant sugarcane

Assuming that growers plant about 54,000 ha (133,434 ac) of sugarcane annually as they did in 1993 (Glaz 1994) and 31.5% is planted in the fallow system, about 17,000 ha (42,000 ac) are available for rice each summer. Snyder et al. (1986a) found that sugarcane following rice had increased yields of 2.2 metric tons (4851 lbs) sugar per ha compared to sugarcane planted in fields not flooded during the summer fallow. Some of this yield increase may have been related to the insect and nematode control provided by flooding rather than to rice, but this was not determined. Rice is being grown on less than 50% of available land in the EAA. A science and extension effort should determine why rice is not planted on 100% of these 17,000 ha annually.

A second opportunity exists to increase the sugarcane-rice rotation. Alvarez (pers. comm.) reports that economic analysis is underway that includes a comparison of successive sugarcane with sugarcane-rice rotation. Glaz and Ulloa (1993) reported successive yields averaged 14-17 metric tons (30,870-37,485 lbs) cane per ha per year less than nonflooded fallow yields for a three-crop cycle (plant crop through second ratoon). The successive rotation is popular because although yields per ha per year are lower, sugarcane is harvested more years than in the fallow system (Table 4). In sugarcane-rice rotation, cane yields following rice are higher than cane yields following nonflooded fallow (Snyder at al. 1986). Therefore, yields would probably increase more than the 14-17 metric tons cane per ha for sugarcane following rice compared to the sugarcane following nonflooded fallow reported by Glaz and Ulloa (1993). Once the economic study is released, if it is necessary and appears reasonable, scientists should make a concentrated effort to improve profitability of the sugarcane-rice rotation to at least make it equal to the successive-sugarcane system. By doing so, an additional 37,000 ha (91,427 ac) could be cultivated with rice and thereby summer flooded.

A third opportunity exists to increase rice hectarage in the EAA. It is difficult to estimate the area grown to winter vegetables in the EAA because many vegetable growers harvest more than one crop per year. Schueneman and Sanchez (1994) estimate the EAA contains about 23,100 ha (57,080 ac) dedicated to winter vegetables. A small amount of this land is already rotated with rice. Some of the hectarage not planted to rice is left fallow during summer and some of this fallow land is flooded during summer.

Many vegetable growers flood for 6 weeks, drain for 2 weeks, and then flood again for 6 more weeks during the summers. This practice has probably evolved from Genung's (1970) work, which determined that flooding for 4 weeks, draining 2 weeks, and reflooding for 4 more weeks provided 100% wireworm control. Later work by Hall and Cherry (1993) reported that more than 6 weeks of continuous flooding would be needed to provide 100% mortality of wireworms. Scientific studies should determine the differences in annual subsidence in fields drained for 2 weeks compared to those flooded for 14 consecutive weeks during summer. During summer fallow periods, growers' primary goal should be to control subsidence rather than wireworms. Control of wireworms and other pests should be considered an extra benefit of controlling subsidence.

Schueneman and Sanchez (1994) discussed cropping seasons for many EAA vegetables. More vegetable growers could probably include a rice crop without upsetting their vegetable cropping patterns. Agronomic studies aimed at reducing growing seasons and time needed for land preparation for both vegetables and rice could help accommodate this cropping sequence. Successful results could increase annual profits for these growers as they reduce soil subsidence.

By using sugarcane-rice, vegetable-rice, and sugarcane- or vegetable-flooded fallow cropping systems, growers in the EAA could flood much of their soils during summer. If only the fallow sugarcane cropping system and the summer-fallow of vegetable fields are considered, 40,000 ha (98,840 ac) could be flooded each year. Thus immediately 19.5% of the EAA could be flooded during the summer wet season. Growers who could include a rice crop in their cycles may increase their annual profits on much of this land. Replacing successive sugarcane with a sugarcane-rice rotation would allow flooding of 37,000 additional ha (91,427 ac) during the summer rice crop. This would allow flooding of 37.5% of the total agricultural land in the EAA during the wet season. This scenario is low-risk because it uses cropping systems already proven profitable and emphasizes maintaining or increasing current profits.

As stated earlier, an important topic related to this approach is the annual rate of subsidence with the sugarcane-rice rotation vs. only sugarcane and the vegetable-flooded fallow or vegetable-rice rotation vs. only vegetables. Optimistically hypothesizing that the annual subsidence rate will approach zero with these flood cropping

systems, there would be a 37.5% reduction of subsidence in the EAA, or a reduction from 3.6 to 2.25 cm (1.4 to 0.9 in) per year (Figure 12). This analysis was based on 205,000 cultivated ha (506,555 ac) per year in the EAA (155,000 ha of sugarcane, 17,000 ha of fallow sugarcane land, 23,000 ha of vegetables, and 10,000 ha of sod); an initial subsidence rate of 3.6 cm per year based on a 60-cm water table; and the Stephens et al. (1984) equation relating subsidence and water table.

Some growers have already initiated these strategies in the EAA, so the annual subsidence rate is probably substantially lower than 3.6 cm. Also, the Stephens et al. (1984) equation may overestimate subsidence rates, as discussed earlier. Therefore, this analysis of theoretical subsidence rates should be used to demonstrate relative differences in subsidence with various strategies, rather than as a precise estimate of EAA subsidence.

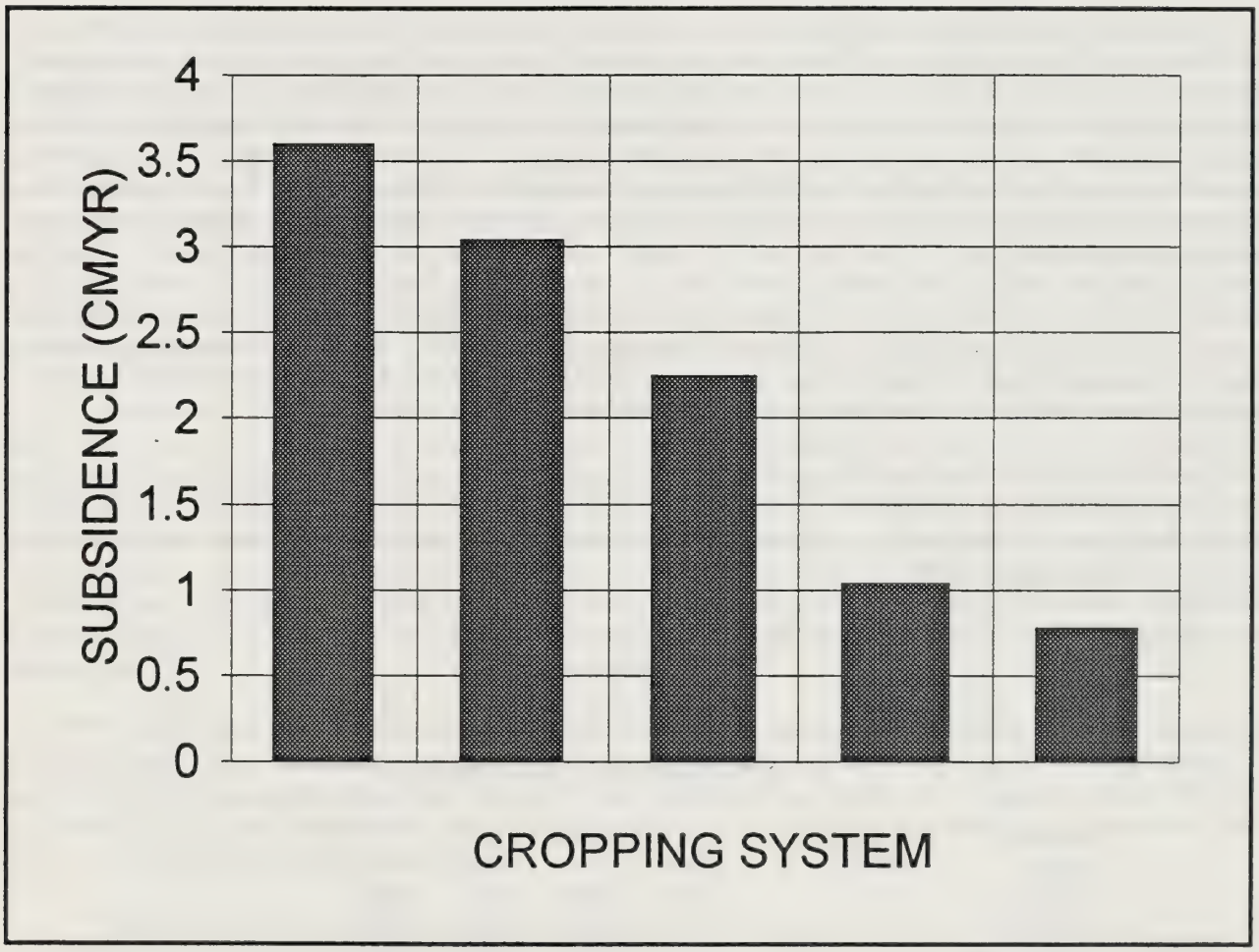


Figure 12. Theoretical subsidence scenarios in the EAA using the equation of Stephens et al. (1984). A: All cultivated soils in EAA at 60-cm water table. B: Same as A except 23,000 ha of winter vegetables summer flooded and 8,815 ha rice summer flooded. C: Same as B except additional 37,000 ha sugarcane available for summer flood. D: Same as C except nonflooded EAA at 30-cm water table. E: Same as D except assumes sugarcane causes 25% reduction in subsidence compared to other crops.

Sugarcane

The ecological and economic benefits of sugarcane to South Florida are often poorly understood. Even within South Florida, where sugarcane has extensive positive economic impacts, it often has less than a positive image. One possible reason is the misconception that sugar, the primary product of sugarcane, is bad for human health. However, research has shown that, unless one suffers from an illness such as diabetes, consumption of sugar at levels common to the U.S. population has no negative health effects except that it contributes to dental caries (Glinsmann et al. 1986).

Sugarcane growers also enjoy less than a harmonious public relationship with groups concerned about restoring natural portions of the South Florida Ecosystem. News media often report demands that sugarcane be removed from the EAA or that sugarcane growers pay directly for all negative environmental impacts they cause. This negative relationship is unfortunate because sugarcane can be an integral component of an ecological restoration program. Sugarcane and rice are the most ecologically sensible of the major crops historically grown in the EAA.

Although there is disagreement on its negative impact, scientists agree that more phosphorus leaves the EAA now than before widespread agriculture was practiced in the subregion. One wonders if those who suggest removing sugarcane from the EAA understand how much worse the phosphorus problem would become if growers replaced sugarcane with other crops or if agriculture was totally discontinued in the EAA. Izuno et al. (1991b) reported less phosphorus was exported from a field cropped to sugarcane than from a field left fallow and suggested sugarcane acted as a nutrient sink. Although sugarcane and vegetable agriculture may have led to some of the ecosystem's phosphorus-related problems, changes in sugarcane agriculture already in place indicate sugarcane can help resolve the problem.

Table 5 is compiled from fertilizer recommendations of Sanchez (1990) for crops historically important in the EAA. All EAA crops except rice required more phosphorus fertilizer than sugarcane. Celery, escarole, and lettuce often required about 10 times as much phosphorus per ha as sugarcane. At a soil test level of 9, escarole required 36 times more phosphorus fertilizer than sugarcane.

Table 5. Phosphorus fertilizer recommendations for crops grown on Histosols in the EAA across a range of soil-test-P index levels (Sanchez 1990).

Crop	Soil-test index levels 3	6	9	12
	kg fertilizer P_2O_5 applied per hectare			
Cabbage	157	90	22	0
Celery	493	426	359	291
Endive	381	314	247	179
Escarole	605	538	471	403
Lettuce	538	471	404	336
Radish (three crops)	247	179	112	45
Radish (one crop)	112	45	0	0
Rice[a]	0	0	0	0
Sod	140	120	60	0
Sugarcane	53	40	13	0
Sweet corn	269	202	134	67

[a]The recommendation for rice by Sanchez (1990) is valid for rice grown in rotation with an adequately fertilized crop. If grown in monoculture, rice may require some phosphorus fertilization (Snyder and Jones 1988a, 1992).

Coale et al. (1993) found sugarcane removed 1.79 times more phosphorus than was applied as fertilizer. Coale et al. (1994a) reported sugarcane removed 23 kg P per ha or 0.22 kg P per ton of sugarcane harvested. Andreis (1975) reported a crop of sugarcane that yields 90 mt cane per ha would contain 13.2 kg P. Izuno et al. (1991) confirmed this work and found sugarcane annually removed about 12.5 kg per ha P from the EAA. Since sugarcane accumulates biomass for a full year before its harvest and much of this biomass is removed at harvest, it is logical that sugarcane can be a tool for removing excess phosphorus from the EAA. Recent work has identified practices to reduce many of the high vegetable fertilizer rates. However, even at these reduced rates, much more phosphorus is applied to vegetables than to sugarcane.

Andreis (1975) also noted that sugarcane cultivars differed in concentrations of phosphorus in their tissue. This lends credibility to the concept of pursuing breeding and selection programs aimed at identifying sugarcane cultivars with various phosphorus uptake capabilities. Glaz and Ulloa (1994) reported further evidence that such a breeding and selection goal could be successful. A group of USDA and UF scientists recently initiated a long-term sugarcane genetics program with this objective.

Another positive ecological characteristic of sugarcane is that it requires small amounts of pesticides. For disease problems, sugarcane growers rely primarily on resistant cultivars. Hall and Bennett (1994) estimated that in 1990 more than 60% of Florida sugarcane fields received no foliar insecticide applications and soil insecticides were typically applied only once every 3-5 years. Many growers have scouting programs to help decide if insecticides are necessary. Hall (1981) recommended spraying for borer control if more than 3% of stalks had borers and less than 50% of the borers were parasitized. Hall (1990) explained that threshold determinations of wireworms rely upon more than just the wireworm population, but he recommended soil insecticides were generally not needed if wireworms were less than 12,000 per ha. Some herbicides are used for weed control; however, once sugarcane covers the rows herbicides are usually not needed. Many growers use shallow cultivation to keep herbicide use to a minimum before sugarcane growth covers the inter-row space. Glaz et al. (1989) found such cultivations were more beneficial in the second-ratoon than the plant or first-ratoon crops.

Snyder et al. (1978) reported sugarcane could tolerate water tables as high as most crops except rice and still produce optimum yields. Due to restoration plans, the EAA may convey more water in the future. Sugarcane offers more flexibility than other crops in formulating a water-management strategy to deal with wetter and sometimes drier conditions of a rain-driven system. Many vegetables and rice need constant water tables to produce high yields of acceptable quality. At some stages of growth, water tables of 0-1.2 m (0-3.9 ft) from the soil surface for short durations probably do not harm sugarcane. Therefore, hydrologists could plan to flood sugarcane fields to store excess water and drain them when other areas need water. Also, sugarcane is primarily planted and harvested during the dry season. With proper water management, these practices could probably continue with minimal impact.

A large sugarcane infrastructure is in place in South Florida. Many trucks, trailers, and trains carry sugarcane to factories. Seven large factories process sugarcane into granulated sugar. Two refineries refine the sugar. Electrical cogeneration plants and plants for other byproducts are in place or planned at several factories. Thousands of people are employed by the sugarcane industry. We are fortunate that sugarcane agriculture offers many of the ecological solutions we seek.

Development of a profitable sugarcane cropping system with no net soil loss should be the primary goal for the EAA for those trying to conserve either the EAA and or the South Florida Ecosystem. This approach to achieving a sustainable agriculture in the EAA has not received sufficient attention from scientists, probably for three reasons: 1) Sugarcane is generally regarded as a crop that does not tolerate flooded conditions (discussed below), 2) the perception exists that organic soils must be flooded 12 months per year to control subsidence caused by oxidation (addressed above under subsidence), and 3) due to increased urban water demands there may not be enough water available to maintain sufficient flooded conditions in the EAA to end subsidence (addressed above under subsidence).

Can sugarcane tolerate floods?

Scientific studies have shown that sugarcane has genetic potential to adapt to a wide range of water tables. Glaz and Kang (1985) reported that relative cane production of 2 of 12 cultivars varied due to differing water tables. Deren, Snyder, Miller, and Pope (1991) found sugarcane cultivars interacted significantly with water tables for such traits as cane and sugar production. These results showed that, for immediate use, some existing cultivars would be better adapted to high water tables than others. For long-term planning, these preliminary studies indicate breeding programs could successfully identify sugarcane cultivars adapted to higher water tables.

In an experiment aimed at insect control, Cherry (1984) reported on effects of flooding sugarcane for 10 days during September or October in commercial fields. He did not compare flooded vs. unflooded fields, but reported the flooded fields were commercially profitable. However, to substantially reduce subsidence, sugarcane fields will need to remain flooded for longer than 10 days. A preliminary study by Deren, Snyder, Miller, and Pope (1991) found that tolerance to floods of longer duration is probably a heritable trait in sugarcane and variability among sugarcane clones for this trait is sufficient to warrant beginning a long-term project to breed and select for flood-tolerant sugarcane. In India, Naidu and Arulraj (1992) reported 14 of 65 cultivars were resistant to "severe conditions of waterlogging." Naidu (pers. comm.) stated that sugarcane in these experiments was subjected to continuous flooding, at times with water 30-60 cm above ground level from mid-June to mid-November.

In a field study testing water tables and sugarcane, Kang et al. (1986) found sugarcane at a 29.8-cm (11.7-in) water table yielded more sugar and cane per ha than at a 56.2-cm (22.1-in) water table. They reported a mean cane yield increase of 26.4% and an increase of 16.7% in sugar concentration at the higher water table. Gascho and Shih (1979) tested five sugarcane cultivars at water tables of 32, 61, and 84 cm (13, 24, and 33 in) from the surface of Pahokee muck soils in lysimeters. Overall, highest yields occurred at the 61-cm water table. Two of the six cultivars yielded equal cane weights at all three water levels. Although not significantly different from the yields at the two deeper water tables, both of these cultivars had their highest cane yields at the 32-cm water table. LeCroy and Orsenigo (1964) studied cane tonnages and sugar concentrations of four cultivars at six water-table depths, ranging from 36.6-88.4 cm (14.4-34.8 in) from the soil surface. All cultivars had respectable yields at the 36.6-cm water table. In addition, they reported variable cultivar responses to water-table depth. Andreis (1976) reported yields of a 4-crop cycle (plant crop through third ratoon) of sugarcane at a 48-cm (19-in) water table equaled those of sugarcane at a 94-cm (37-in) water table. Andreis further found that yields in the 48-cm water table were more favorable in the first three harvests compared to the fourth harvest (third ratoon).

In a summary of several experiments in Louisiana (Carter 1980, 1986; Carter and Camp, 1983; Carter and Floyd 1970, 1975; Carter et al. 1970, 1988a,b, 1992), Carter (pers. comm.) reviewed water table and sugarcane relations. Floods can be maintained by stagnant water or constantly inflowing and outflowing water. Since water movement in contact with air increases oxygen content of the water, one would expect sugarcane to do better in moving rather than stagnant water. Scientific study must determine if the oxygen concentration in moving water is sufficient to support substantial oxidation by microorganisms. One source for optimism comes from Andreis (1976) who reported water had to be pumped in often to maintain water tables, but subsidence was much less than that predicted by the equation of Stephens et al. (1984). Reddy (1987) noted flooding in organic soils can be conducive to growth of algae. Since these algae photosynthesize, which elevates oxygen, they may reduce the anaerobic conditions of the soil.

Carter (pers. comm.) also felt that consistency of water table, to a point, may be more important than depth of water table. He suggested sugarcane may do well at water tables at 30 cm or closer to the soil surface if this water table does not fluctuate for long periods. However, Carter and Floyd (1975) also reported that high water tables would be most successfully maintained during April to October, rather than during cool winter months. This fits well with the rain-driven approach to reducing subsidence because April to October is when water is naturally available in the EAA, and theoretically, to control oxidation, it is more important to cover soil with water during these warmer months when microorganisms are most active.

In a review of sugarcane root growth, Gascho (1985) reported roots 400 cm (13 ft) deep in one region with dry, well-drained soils. However, other reports cited by Gascho indicated 60% of sugarcane roots were within 20 cm (8 in) of the soil surface and more than 85% of roots were within the upper 40 cm (15.7) of soil. Andreis (1976)

reported sugarcane had greater total root weight when grown with a water table 48 cm from the surface compared to 94 cm from the surface. This vast range of root growth is undoubtedly a major reason for sugarcane's successful adaptability to a wide range of moisture conditions.

Additional reports from Florida and other regions indicate some sugarcane cultivars adapt well to floods of at least minimum duration (Burgess 1991; Naidu and Arulraj 1992; Negi et al. 1971; Roach and Mullins 1985; Stevens, 1948). Two programs in Florida breed and select sugarcane cultivars: 1) a cooperative program of the USDA-ARS, IFAS, and Florida Sugar Cane League, Inc.; and 2) a program of U.S. Sugar Corporation.

Short-term sugarcane studies

The most important short-term objective should be to test current commercial-type cultivars at several water tables. Those doing best under flooded conditions could be used as parents in the long-term program and utilized immediately for biparental crosses. Based on Kang et al. (1986), LeCroy and Orsenigo (1964), Gascho and Shih (1979), and Andreis (1976), some commercial cultivars may yield at least as well at a 30-cm compared to a 60-cm water table. If studies identify such cultivars, growers could use them immediately without losses in productivity. According to the Stephens et al. (1984) equation, this would reduce subsidence by 53%. Combining this with the earlier proposed 37.5% reduction due to summer flooding, EAA subsidence could be reduced by 71.1% to an overall rate of 1.04 cm (0.4 in) per year (Figure 12). Factoring in the suggested 25% reduction in subsidence due to sugarcane, the theoretical EAA-wide subsidence rate is reduced to 0.78 (0.3 in) cm per year.

Growers in the EAA have already initiated many of the changes suggested here. The short-term scenario proposed in Figure 12 with subsidence declining to 1.04 cm or 0.78 cm per year is not a major change from EAA agricultural conditions of today. However, achieving this type of agriculture would be a major short-term gain in maintaining a profitable agriculture and controlling subsidence in the EAA. Achieving these realistic goals would more than triple the life of EAA agriculture. If the 25% reduction due to cropping sugarcane proves factual, the life of these soils would be extended by a factor greater than four.

Long-term sugarcane studies

One long-term sugarcane project should aim at breeding and selecting cultivars adapted to water tables closer to the soil surface than 30 cm. This will involve identifying parents, evaluating progeny, and quantitative genetic studies. Normal sugarcane selection cycles in Florida, from parental crosses to cultivar releases, take 9-11 years. Therefore, substantial improvements in this characteristic could take many years. However, we could expect gradual improvements. We should not expect suddenly after 25 years of study to identify a sugarcane cultivar that withstands flood for 7 months. Instead, we should expect to gradually identify cultivars adapted to higher water tables for longer durations.

Some of the new breeding procedures that operate at the molecular level could complement the conventional breeding approach in producing sugarcane cultivars adapted to higher water tables. No work in this area is underway in Florida or related to producing sugarcane clones adapted to high water tables. However, the FSCL supports the International Consortium of Sugarcane Biotechnologists, and scientists supported by the ICSB are currently doing genetic mapping (RFLP analysis and restriction maps) and transferring genes from other plants to sugarcane in France, Brazil, Australia, and other countries as well as Louisiana, Texas, California, and Hawaii.

These new areas of biotechnology offer enormous potential. However, concrete benefits with sugarcane would probably be very long-term. With other crops whose genetics are better understood, minor gains have been achieved through molecular biology. These gains have often been due to genetic studies that identified specific functions of single genes. Sugarcane genetics are very complex and poorly understood, and effects of individual genes are unknown. Genetic studies of sugarcane are normally quantitative in nature, but even these do not fit classic Mendelian theories due to the poorly understood polyploid nature of sugarcane.

The concept of breeding and selecting sugarcane cultivars adapted to higher water tables is not new among agricultural scientists in the EAA. The work already initiated in Florida has produced promising results. To continue this work and obtain results sufficiently reliable for successful commercial production, scientists need initial funding

to construct several locations with replicated plots of several water tables. Agricultural scientists in Florida have a long and unsuccessful history of seeking such funding. This list of unsuccessful proposals includes, but may not be limited to: Coale and Deren (1992); Deren (1990, 1991a,b); Deren, Snyder, and Miller (1989, 1991a,b,c); Deren, Snyder, Miller, and Porter (1989); Gill et al. (1979); Izuno et al. (1990); Kidder et al. (prior to 1978); Nuessly et al. (1990). Scientists who comprise the cooperative sugarcane breeding program in Canal Point have already modified that program to the extent possible without additional support. Their immediate goal is to make all selections from the early stages of their 4-stage, 9-year program at 30-cm water tables.

Equally important to the long-term breeding project is the need to do agronomic/microbiological studies related to sugarcane and subsidence. Although sugarcane scientists are confident they can breed and select cultivars adapted to higher water tables, even the most optimistic researchers doubt they will find sugarcane cultivars that produce well in floods of 6-7 months duration. Therefore, as breeders improve water tolerance in sugarcane, agronomists/microbiologists must pursue a water-management system that will produce optimum sugarcane yields while minimizing subsidence. As breeders take sugarcane to its biological limits for tolerating flood, agronomic and microbiological work should determine the least magnitude and duration of flooding needed to control subsidence while growing sugarcane profitably.

This work should begin by rigorously testing the assumption that sugarcane can tolerate floods of short duration without suffering yield losses. Concurrently with this, the stage of growth at which sugarcane best tolerates floods and the changes in sugarcane production as height of water above the surface increases should be determined. Once benchmarks are determined for these characteristics, breeders can attempt to improve upon them. Work should then determine how long and to what depth water tables can be lowered before appreciable oxidation resumes. With this knowledge, scientists would then need to determine how long and to what depth sugarcane should be drained before reflooding will not harm its growth. The ultimate goal would be to determine a water-management strategy under which sugarcane would thrive, but subsidence due to oxidation would not occur. These efforts would also improve our knowledge about the effects of variable water tables on subsidence.

Microbiological investigations should also pursue the suggestion that crops such as sugarcane and alfalfa may release toxins from their roots that inhibit microorganisms from causing oxidation. The first step would be to determine if sugarcane roots release such toxins and their effectiveness. If promising, geneticists could include among their goals the identification of cultivars that release more of these toxins. Although extremely preliminary, this is a logical science topic based upon findings that sugarcane inhibits subsidence. If successful, this work could offer an additional mechanism for achieving zero-subsidence agriculture in the EAA.

Other areas in which scientific studies will probably be needed are sugarcane pathology and entomology. With continually higher water tables and roots at times submerged in water, certain pathogens naturally controlled under current conditions may cause economic damage. In particular, *Pythium* and *Phytophthora* species may become more abundant under proposed wetter conditions (Comstock, pers. comm.). Extensive flooding will probably cause population changes among insect species in the EAA. Future entomological work should try to maintain favorable balances of insect pests and their predators and assure new insect pests do not emerge.

Vegetables

Schueneman and Sanchez (1994) estimate the EAA contains about 23,100 ha (57,080 ac) of winter vegetables. As stated earlier, vegetables need much higher amounts of phosphorus fertilizer than sugarcane and rice, cannot withstand as high a water table as sugarcane and rice, and cannot withstand fluctuations in water table as well as sugarcane. Scientists should aim to improve these characteristics for vegetables. A key advantage of vegetables is they are annual crops grown primarily during the winter dry season. Thus, most growers should be able to maintain summer floods or rice crops without compromising their vegetable crops.

Most winter vegetables in the EAA probably are not genetically capable of producing well with water tables as high as sugarcane can tolerate. Still, breeders should be encouraged and supplied proper facilities to breed vegetable cultivars capable of withstanding water tables higher than those currently used. The EREC in Belle Glade, Florida, currently has breeding programs for lettuce, celery, and sweet corn. Scientists should also determine ways

to utilize much of the residual phosphorus applied to vegetable fields for subsequent sugarcane, rice, or vegetable crops. Izuno (pers. comm.) currently is conducting investigations in this area.

All vegetables do not receive equal amounts of pesticide applications. Radish, a crop with a rapid turn-around time, rarely requires pesticides. Sweet corn may receive two insecticide applications per week after silking. Several vegetables require preventive fungicides at regular intervals, because once certain diseases successfully infect a plant, their populations can explode across fields. Within the last 15 years, scouting has become an accepted practice for insect control on many vegetable crops and has reduced insecticide use substantially in the EAA. Threshold levels that could be used in conjunction with scouting for insect control need to be more precisely determined. Comprehensive models that require inputs of market, biological, and environmental factors could help vegetable growers make daily decisions on insecticide use.

Sod

Cisar et al. (1994) provide a summary of sod production in the EAA. Approximately 10,000 ha (24,710 ac) of sod were produced in the subregion in 1990. This accounted for about 50% of Florida's sod production. Sod production causes soil loss by mechanical means in addition to the loss by subsidence. Soil loss per harvest, every 10-12 months, ranges from 0.6-1.25 cm (0.2-0.5 in). This range is due to the type of harvesting machinery and sod and soil conditions at harvest. Water tables remain relatively high in sod, from 30-76 cm (12-30 in) from the soil surface. Sod could probably withstand higher water tables, but as the water table gets above 30 cm the soil is not sufficiently firm to support heavy machinery used for mowing. As shown in Table 5, sod requires more phosphorus fertilizer than sugarcane and rice but less than most EAA vegetable crops.

Priorities for efforts to make sod production more sustainable include development of harvesters that extract less soil, determination of harvesting conditions that extract the least amount of soil, development of machinery capable of mowing at higher water tables, development of more flexible mowing schedules to lessen the constraint of mowing on water-table management, and water-table management that permits higher water tables during periods requiring less frequent mowing.

Alternate Crops

The major thrust of science in the EAA should be to make current commercial crops more ecologically compatible without losing profits. However, studies on alternate crops should not be ignored. Perhaps a market will never develop for some of these crops. On the other hand, market conditions may change for crops now grown in the EAA. Also, crops grown in monoculture often develop serious pest problems. Sugarcane has developed disease, insect, and weed problems. Pathologists, entomologists, agronomists, and geneticists often plan much of their work around these issues. Evidence from other rice-growing areas indicates rice as a monoculture may present more serious pest problems than sugarcane. Investigations on alternate crops should concentrate on crops similar to rice that thrive under flooded conditions during EAA summers but do not suffer devastating yield losses if not flooded for short durations. Also, study should concentrate on crops whose estimated ETs do not exceed long-term average EAA rainfall.

Alternate crops may individually never account for large amounts of EAA area. However, if growers develop small markets for several crops, perhaps as a group alternate crops could play an important role. Jones et al. (1994) summarize work on water spinach, water celery, taro, Chinese water chestnuts, and lotus. These crops have grown well experimentally in the EAA. To grow them commercially, they would need expanded markets. Wild rice may already have a sufficient market for some commercial production, but available cultivars do not yield at commercially profitable levels in the EAA. Jones et al. (1994) suggest that geneticists try to develop wild rice cultivars adapted to the EAA. Taro, alemangrass, and paragrass offer potential as biofuel crops if prices of present fuel sources rise.

Phosphorus and Agriculture

LOTAC I (1986) reported that phosphorus from agricultural drainage was a contributing factor to accelerated eutrophication of Lake Okeechobee. Canfield and Hoyer (1988) and Maceina and Soballe (1990),

however, proposed that the noted eutrophication was due to causes other than agricultural drainage. Another concern was that elevated phosphorus levels in areas of the WCAs near entry points of agricultural drainage water were causing an unnaturally high level of cattail (*Typha latifolia* L.) growth compared to sawgrass (*Cladium jamaicense* L.) (LOTAC II 1990). The SFWMD (1992a) cautions several factors can influence expansion of cattails in the Everglades. Among these are "physical disturbance of underlying soil profile (by canal construction activities or by alligator nest building), proximity to seed sources, fire, hydrologic changes and the availability of nutrients."

Reddy et al. (1993) and Whalen et al. (1992) stated that EAA drainage waters entering Loxahatchee NWR contained phosphorus concentrations up to 20 times higher than those measured at interior sites within the refuge. They also reported drainage from the EAA accounted for 47%, or 205 metric tons (452,025 lbs) per year, of all phosphorus flowing into the system and rainfall accounted for an additional 40%. Anderson and Howell (1993) calculated theoretically the EAA was responsible for 51.9 mt (114,440 lbs) P per year transported to the Everglades Protection Area.

Two major programs are in place to lower the phosphorus content of EAA drainage water entering the WCAs. One is use of BMPs pursued by IFAS and private growers, which receives much support from the Everglades Protection District. The other is a SFWMD program to determine the utility of up to 16,200 ha (40,030 ac) of STAs as described by Whalen et al. (1992).

Soil subsidence is potentially a major source of phosphorus in agricultural drainage waters coming from the EAA (Hortenstine and Forbes 1972). Morris (1975) estimated subsidence generated 87 kg P per ha per yr, or 400% of the average rate of fertilizer phosphorus applied to sugarcane (Sanchez 1990). Reddy (1987) reported oxidation causes release of 38-185 kg P per ha per year. Therefore, controlling subsidence and phosphorus should generally be consistent objectives. However, in the short term, phosphorus runoff may increase due to control of subsidence (Sanchez and Porter 1987). For the long term, scientists must determine effective phosphorus control strategies within the framework of an agriculture with substantially less subsidence.

Background levels of soil phosphorus in organic soils cropped to sugarcane ranged from 90-330 mg P per liter (CH2M Hill 1979). This range encompasses the average values for organic soils of 0.01-0.3% of the soil reported by Lucas (1982). Diaz et al. (1993) reported phosphorus levels of 279 μg P per cm^3 of soil for an uncultivated Pahokee muck and similar levels for cropped Pahokee and Lauderhill mucks. For an Okeelanta muck they reported 156 μg P per cm^3 and for a Torry muck 1737 μg P per cm^3 of soil. Reddy (1983) reported Florida's central and southern organic soils released from 16-168 kg P per ha into effluent. This accounted for 0.75-1.1% of total soil phosphorus of the organic soils in southern Florida. The SFWMD and EAA landowners already have an elaborate system to monitor phosphorus leaving farms in the EAA (Germain and Shaw 1988; SFWMD 1992b; Whalen 1992). This monitoring will be carried out in District Works within the EAA and STAs as well as for water leaving individual farms.

Phosphorus nutrition of crops is a complex issue. Bohn et al. (1985) stated: "The chemistry of phosphate in soils has been studied more intensively than that of any other mineral nutrient except nitrogen. Despite the great effort, little definitive can be said about the state of phosphorus in soils: The uncertainties about phosphate chemistry in soils are due to phosphate's strong interaction with many inorganic and organic solid phases, continual uptake by plants and microorganisms, continual return from organic decay, and slow reaction rates." They were referring generally to aerated mineral agricultural soils. The chemistry of phosphorus is less understood in aerated organic soils and becomes more complex in inundated organic soils.

Phosphorus has become an even more complicated issue as it relates to restoration of the South Florida Ecosystem compared to its effects only on agriculture. We must not only understand how to most efficiently utilize phosphorus to the advantage of agriculture but also must devise hydrological systems that reduce the amount of phosphorus leaving agricultural soils and tend not to transport phosphorus that has left the soil. We also need a much clearer understanding of the biological impact of phosphorus on natural portions of the ecosystem.

As shown in Table 5, up to 605 kg per ha of P_2O_5 has been recommended for agricultural crops in the EAA. The interim goal is to reduce phosphorus in water leaving the EAA to 50 parts per billion. If no further

investigation is done to determine acceptable levels in the WCAs, phosphorus in EAA runoff water will have to be reduced to 10 parts per billion.

Scientists in the EAA began pursuing solutions to the phosphorus issue several years ago. Soil scientists, agricultural engineers, hydrologists, geneticists, plant pathologists, and scientists from other disciplines have been involved. To best deal with the brief but rich history and interdisciplinary and complex nature of the phosphorus issue, a meeting of knowledgeable scientists was held at Belle Glade, Florida, on April 14, 1994. The purpose of this workshop was to outline a comprehensive science plan with the goal of reducing phosphorus runoff from the EAA to the WCAs. Participants listed important issues related to phosphorus export from the EAA, and for each issue identified completed and ongoing projects and topics where scientific study is still needed. This workshop was a preliminary attempt to quickly summarize important work and identify science needs related to resolving this complex issue. Perhaps the most important recommendation is the need to hold more detailed workshops on several issues identified at this workshop. These workshops will often need to be interdisciplinary and include scientists whose major interests are in the EAA, WCAs, or Lake Okeechobee.

Results of the workshop are summarized below, with completed, ongoing, and proposed projects listed under each issue. This summary does not prioritize scientific information needs. Names in parentheses refer to either published citations or the person who volunteered the statement. Appendix A to this chapter is a list of workshop participants. Dr. D.L. Anderson supplied a thorough literature review on phosphorus issues (Appendix B), Dr. F.T. Izuno provided a summary of BMPs and hydrological issues (Appendix C), and Dr. K.R. Reddy supplied a summary of science needs for STAs (Appendix D).

- **Sediments/other particulates**

Completed

1. Contributes 50-80% of P transported from EAA canals. (Anderson)
2. Initially quantified particulate P ratios. Work is also ongoing. (Izuno)
3. Small-scale effect of drainage rates on P concentration of canal water (Coale et al. 1994). Izuno et al. (1991b) found that fast-drained plots had lower total P and lower total dissolved P than slow-drained plots. They were not comfortable with this result. Work is also ongoing.
4. Effect of cleaning sediments from canals and spreading on fields as BMP. Work is also ongoing. (Izuno)
5. Distribution of total P in primary canals. (Anderson)
6. Use of minimum tillage to reduce sediments and thus P concentration in canal water. (Andreis)
7. Chemical treatments to precipitate P in farm and basin canals. Results showed it is effective but has high initial and continuous costs. (Anderson)
8. On-farm ponded water storage maintenance. Promising results. (Anderson)
9. Soluble orthophosphorus accounted for 54-57% of effluent P for South Florida organic soils (Reddy 1983).

Ongoing

1. Characterization of particulates and sediments. (Stuck)
2. Evaluation of efficiency of ditch cleaning as a BMP. (Barber may be able to supply citation.)
3. Transportability in canals and marshes of various forms of sediments containing P. (Richardson may be able to supply citation.)
4. Identification of characteristics that cause a farm to be a net loader or assimilator.

Proposed

1. Monitor P levels, dissolved and particulate, in farm and SFWMD canals. Need to determine relative importance of sources of P in canals (wind, algae, etc.)
2. Investigate soil P chemistry.
3. Determine origin and composition of sediments.
4. Investigate long- and short-term biological availability of identifiable forms of P.

5. Investigate chemical precipitation and coagulation for dephosphorization. Include feasibility of application of residues to commercial fields.

6. Evaluate use of rock pits and chemicals as sediment traps.

7. Conduct cooperative studies with scientists from the Netherlands. (Anderson)

8. Determine erosion index for organic soils.

- **Sources of water: rain and Lake Okeechobee**

Completed

1. More P enters the EAA in water from rain and Lake Okeechobee than leaves in EAA drainage water. (Izuno)

Ongoing

1. FSCL has installed four new stations to measure rainfall to improve distribution of locations. More are needed, as described below.

Proposed

1. Monitor P content in canal water as it enters and leaves individual farms.

2. Quantify amount of P coming into EAA from Lake Okeechobee.

3. Construct water budgets that identify and quantify incoming and outgoing water. Should include surface discharges, seepage (as affected by water depths in Lake Okeechobee and WCAs), ET relationships refined due to water depth and cropping system. To properly build these models, more and better distributed rainfall measurements are needed and should measure both intensity and frequency. These models are needed both EAA wide and at the individual farm level.

4. Compare dryfall and wetfall P.

- **Subsidence/oxidation/mineralization**

Completed

1. Total P liberated from flooded cultivated Histosols was twice that from drained cultivated Histosols. About 6.4 times more P was liberated from an uncultivated Histosol with a fluctuating compared to a constant water table (Diaz et al. 1993).

2. Sanchez and Porter (1987) reported that 20-150 kg P per ha was contained in the soil mineralized annually in the EAA. Reddy (1987) reported 38-185 kg P per ha mineralized annually.

3. No difference in P exported from a field with low rates of fertilizer and cropped to sugarcane vs. a field with no added fertilizer and left fallow. Apparently amount of P lost due to subsidence was the major factor for each field. (Izuno)

4. Reported mass balances for sugarcane, radish, and radish-rice-cabbage systems. (Izuno and Coale)

5. Calculation of P in trash and sugarcane sent to mill. (Andreis)

6. Up to 54.4 kg (120 lbs) per acre per year released due to subsidence (Sanchez and/or Coale).

7. Total P content for uncultivated field < sugarcane field < rice field or fallow field < vegetable field or pasture < horticultural field (Nicholson 1983).

8. Total P about 6.7 times higher in Torry than Pahokee or Lauderhill muck. Total P about equal in cropped or uncropped Pahokee mucks (Diaz et al. 1993).

9. Coale et al. (1993) estimated a sugarcane crop accumulates about 40 kg P per ha per year, which ranges from a little more to less than half of the P mineralized by soil oxidation.

10. Approximately 80-90% of mineralization of organic matter is due to microbial oxidation (Anderson 1994).

Proposed

1. Short-term: Calculate P and other nutrient fertilizer recommendations for growing crops at higher water tables.
2. Long-term: Continuously calibrate nutrient recommendations as soil reserves of these elements change after soils are cropped under higher water tables and flooded conditions for several years.
3. Identify mechanisms relating to P retention and availability.
4. Partition P sources and uses. Phosphorus may have different characteristics depending upon its source and use. This could lead to new soil classification maps.

▸ **Flooding and phosphorus**

Completed

1. Flooding increases P concentration in drainage water by about 4-8 times compared to drained conditions (Reddy 1983) and increases P availability (Reddy 1987).
2. Water between soil pores has 10-15 times more P than flood water. (Anderson)
3. P concentration in soil decreases with soil depth. (Izuno)
4. In the short term, flooding will result in drainage water with higher P concentrations. With long-term flooding, it is likely P content of drainage waters would decline (Sanchez and Porter 1987).
5. Rate of soluble P production in soil under anaerobic conditions was 0.016 g P per m^2 per day. Flux of P as a result of diffusion was about 0.0098 g P per m^2 per day (Reddy and Rao 1983).
6. Losses of P due to mineralization of organic P, adsorption-desorption of P, and diffusion of underlying sediment to overlying water accounted for 53% of the solubilized P.
7. The three most important physiochemical properties affected by flooding are pH, oxidation-reduction potential or redox potential, and ionic strength or salt concentration. Data on pH of flooded organic soils are not available. Redox potential is a measure of electron availability. Well-drained organic soils have redox potentials > 300 mV and this drops to as low as -350 mV in flooded organic soils. Flooding organic soils causes an increase in the amount of ions present in soil solution (Reddy 1987).
8. Flooded fallow fields yielded extremely high P concentrations during draindown (Izuno et al. 1991b).
9. Since rice is a harvested commodity, it results in an export of P from the EAA (Izuno et al. 1991b).

Ongoing

1. Especially as related to rice production, water management effects on P concentration of drainage water. (Izuno)

Proposed

1. Develop basic understanding of P cycling, including P retention and availability as related to P and soil properties.
2. Determine effects of percolation on P.
3. Determine tolerance to flooding (timing and duration) of stages of growth in sugarcane in order to design a strategy in which water high in P can be released onto sugarcane fields for nutrient removal before being pumped off farm.
4. Determine differences among sugarcane cultivars in responses to floodwater high in P.
5. Determine effectiveness of the BMP of flooding sugarcane with water high in P.
6. Determine hydraulic designs necessary to move and store water among fields. This is necessary both at the farm and EAA levels.
7. Develop methods to minimize impact of flooding on planting and harvesting crops.
    a. Harvesting rice under flooded conditions.
    b. Water management strategies to drain flooded fields for harvest or planting.
    c. Use of air seeding to plant rice under flooded conditions.
8. Determine ETs for various crops under different flooding cycles and effect of changing ET on P export.

9. Develop design and determine feasibility of use of on-farm water retention and storage both for farm and WCA needs.

10. Compare surface water storage to storage in 50- to 60-ft deep aquifers.

▸ Wind erosion

Proposed

1. Determine relative importance of sources of wind erosion (e.g., dust from cultivating soil and dust from roads) to total P load.
2. Quantify effect of water-table depth on wind erosion.
3. Quantify effects of minimum tillage on wind erosion.
4. Evaluate use of wind breaks.

▸ Hydraulic control

Completed

1. Prediction of P discharge from fields with different pumping rates. (Bottcher)
2. Model that describes field drainage and P transport. Model includes crops, fertility, porosity, soil moisture, seepage, spatial distribution, ET crop coefficients, and weather data. It is a full water budget at the field scale. A project is now underway at the farm scale. (Izuno)
3. For reservoir soil, about 70 and 76% of floodwater P was removed under aerobic and anaerobic water column conditions, respectively. For flooded organic soil, 51% of aerobic floodwater P was removed after 2 days of incubation, followed by an increase in soluble P concentration of the overlying water, whereas about 64% of anaerobic floodwater P was removed during a 29-day incubation (Reddy and Graetz 1981).
4. Use of biological filters. Reddy et al. (1982) reported on use of water hyacinths, *Elodea*, and cattails in reservoirs to filter P and nitrogen.
5. EAA P loading varied from 0.1-2.9 kg per ha per year (Izuno et al. 1993).

Ongoing

1. Development of sets of site-specific dynamic on-farm models to predict P concentrations. Model to include such factors as hydrology and chemistry of canals and drainage ditches, drainage rates and duration, and solubility of sources of P. (Stuck)
2. P-loading profiles, for particulate and dissolved P, as functions of pumping duration and speed.

Proposed

1. Determine ways to better coordinate pumping by SFWMD and farmers basin-wide.
2. Determine effect of cropping shallow soils on hydraulic practices necessary to reduce P export.

▸ P in canals

Completed

1. 10-year data that quantify P levels in various canals and expected canal loadings.
2. Use of aquatic vegetation in canals to harvest and spread on fields (Reddy).
3. EAA baseline P concentrations at 0.06-0.62 mg per liter (Izuno et al. 1993).
4. Main-farm and SFWMD canals had lower P concentrations than those found in farm fields (Izuno et al. 1991a).

Ongoing

1. Impact of vertical canal profiles on P removal. (Stuck)

Proposed

1. Measure interflow between SFWMD main canals and farm canals. A major issue is to determine effects of one farmer's exported water to the main canals on other farmers' imported water from the main canals.
2. Determine effects of P content in canals on P release and control of oxygen content in canals.
3. Determine effects of nutrient recycling of vegetation.

▸ Stormwater Treatment Areas

Workshop participants recognized the SFWMD is in the process of planning and carrying out studies to determine how to best utilize STAs to remove or filter out P before it arrives at the WCAs. The STAs will eventually be owned by the State of Florida, and probably their use will incur a cost to the State. Therefore, low-profit or negative-profit agricultural systems may be the most efficient and least costly means of utilizing STAs. An advantage of an agricultural approach in these areas is that some P would be physically exported from the ecosystem in the harvested biomass of the crop. Wetland agricultural systems identified included forage crops, tree crops (fast-growing cypress), and a rice-crawfish system.

▸ Fertilizers

Completed

1. Up to a 50% reduction in P fertilizer on lettuce was achieved by applying fertilizer in a band rather than broadcasting it. (Sanchez)
2. Soils with higher pHs tend to tie up P more than soils with low pHs (Anderson). P deficiency is associated with low pH organic soils (Anderson 1989).
3. Use of vesicular-arbuscular mycorrhizae to enhance P utilization by celery. Plants infected with mycorrhizae in a greenhouse study contained 56% more tissue P than those not infected (Datnoff, Raid, Sanchez, and Sommerfeld 1992).
4. Identification of a sweet corn variety that uses P more efficiently than others. (El-Hout)
5. EAA growers already remove 179% of their P fertilizer and 201% of their potassium fertilizer. P export from sugarcane fields has been reduced to 0.37 kg per ha per year. (Izuno)
6. P fertilization plus fertilizer P greatly exceeds P requirements of some crops. (FSCL 1978 in Porter et al. 1991)
7. The maximum P fertilizer recommendation for sugarcane on soils requiring high P fertilizer is less than half the rate of soil P mineralization (Coale et al. 1994a).
8. P fertilizer applied to sugarcane did not affect drainage water P levels (Coale et al. 1994b).
9. Fertilizer recommendations for Florida sugarcane range from 0-37 kg P per ha for the plant crop, 0-35 kg per ha for first-ratoon crops, and average 20 kg per ha for second-ratoon crops (Anderson 1989).

Ongoing

1. Quantification of benefits in reducing P export from fields achievable by banding lower rates of fertilizer compared to broadcasting higher rates. Now being done for cabbage. (Izuno).
2. Breeding and selecting sugarcane cultivars adaptable to various levels of P fertility. (Glaz, Deren, Miller, and Snyder)

Proposed

1. Continue work with mycorrhizae to increase efficiency of P fertilizers as described by Datnoff et al. (1991) and for crops other than celery.
2. Increase efforts to breed and select sugarcane cultivars adaptable to various P levels and similar programs for other crops grown in the EAA.
3. Evaluate use of soil bedding to reduce fertilizer rates and P runoff.
4. Identify sources of P fertilizer that can be used most efficiently by crops with the least runoff.

5. Conduct long-term and evolving soil-testing/calibration studies to identify optimum P rates for combined crop yield and environmental goals as EAA gradually changes to a zero-subsidence agriculture.

- **Urban areas within EAA**

Completed

1. The EPD has installed aquifer storage and recovery wells for Belle Glade and Pahokee. These have reduced P export by 4.5-13.6 mt (9,922-29,988 lbs) per year.

Proposed

1. Identify and quantify urban sources of P.

- **Cropping systems**

Completed

1. P runoff from a fallow field was the same as P runoff from a sugarcane field. (Izuno)

Proposed

1. Identify times of year when most P runoff occurs and develop cropping systems to reduce P runoff at these times.
2. Investigate seeding rice under flooded conditions.
3. Investigate crop rotations for vegetables that require high P inputs to reduce the potential negative impact of these high fertilizers.

- **Controlled burning of sugarcane**

Ongoing

1. Determination of where and in what quantities ash from sugarcane burns falls.

Proposed

1. Construct a P budget that quantifies amount of P contributed to ecosystem by burning, amount of dryfall P from atmosphere, and amount of P in rainfall across EAA.

- **Sugarcane mills**

Proposed

1. Construct a P budget to account for all P that comes into the mill in sugarcane and leaves in sugar, molasses, filter cake, mill boiler, ash from boilers, and other sources.

INFORMATION NEEDS

The scientific information needs for Subregion 4, along with the goal and objectives (SSG 1993), are shown in Figure 13. Recommended science tasks are:

- **Construct facilities in at least three field locations, which will allow for control of three water-table levels in replicated experiments.**

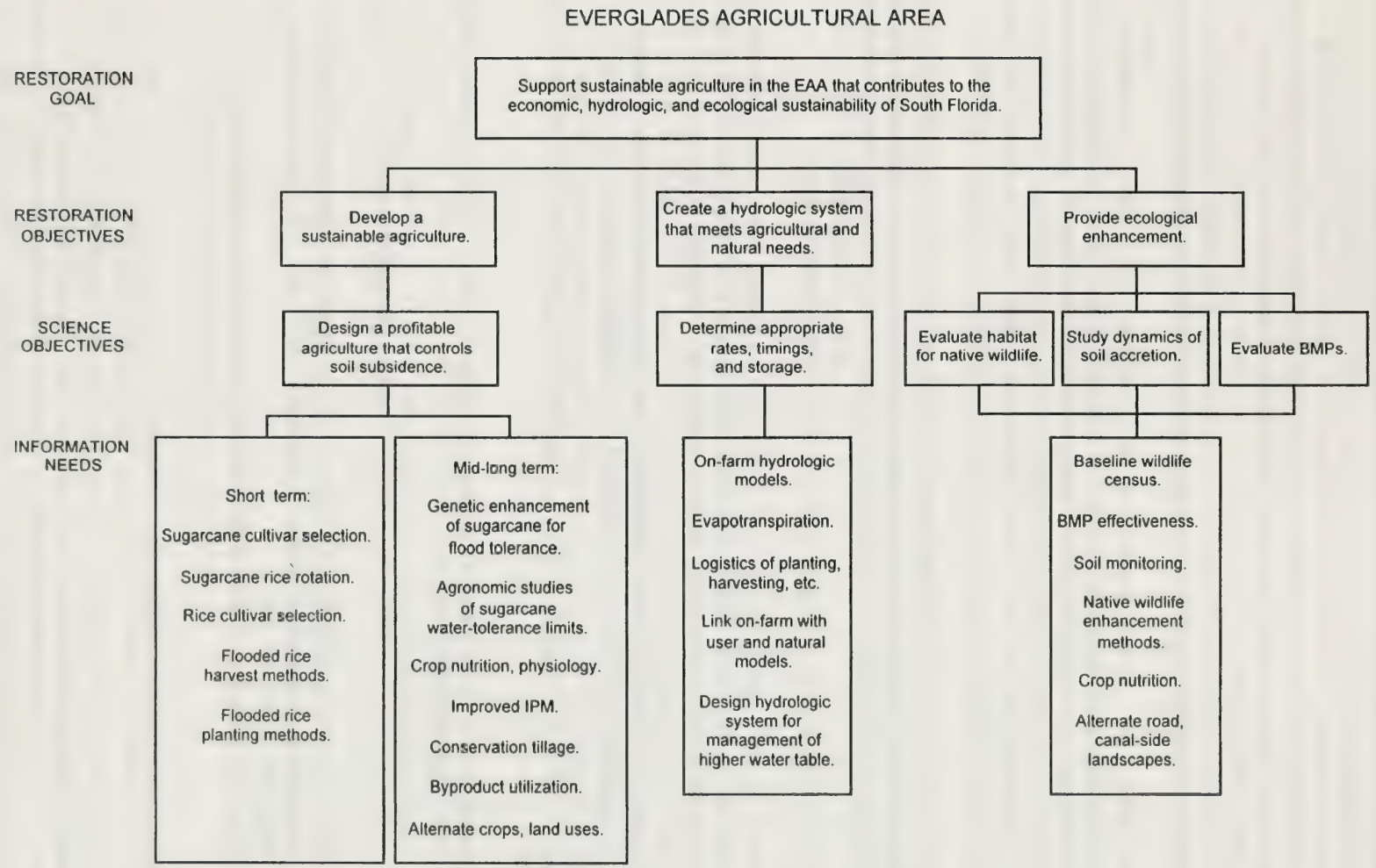

EVERGLADES AGRICULTURAL AREA
RESTORATION GOAL
Support sustainable agriculture in the EAA that contributes to the economic, hydrologic, and ecological sustainability of South Florida.
RESTORATION OBJECTIVES
Develop a sustainable agriculture.
Create a hydrologic system that meets agricultural and natural needs.
Provide ecological enhancement.
SCIENCE OBJECTIVES
Design a profitable agriculture that controls soil subsidence.
Determine appropriate rates, timings, and storage.
Evaluate habitat for native wildlife.
Study dynamics of soil accretion.
Evaluate BMPs.
INFORMATION NEEDS
Short term:
Sugarcane cultivar selection.
Sugarcane rice rotation.
Rice cultivar selection.
Flooded rice harvest methods.
Flooded rice planting methods.
Mid-long term:
Genetic enhancement of sugarcane for flood tolerance.
Agronomic studies of sugarcane water-tolerance limits.
Crop nutrition, physiology.
Improved IPM.
Conservation tillage.
Byproduct utilization.
Alternate crops, land uses.
On-farm hydrologic models.
Evapotranspiration.
Logistics of planting, harvesting, etc.
Link on-farm with user and natural models.
Design hydrologic system for management of higher water table.
Baseline wildlife census.
BMP effectiveness.
Soil monitoring.
Native wildlife enhancement methods.
Crop nutrition.
Alternate road, canal-side landscapes.

Figure 13. Goal, objectives, and information needs for Subregion 4.

- **Using facilities described above, identify commercial and near- commercial sugarcane cultivars best adapted to high water table.**

Sugarcane in the EAA is grown at an average water table of about 60 cm. Past research suggests that of the 40-50 commercial and near-commercial sugarcane cultivars some would probably yield at least as well at an average water table of about 30 cm.

- **Using facilities described above, conduct agronomic/microbiological investigations with sugarcane.**

Agronomic studies on sugarcane should determine duration of flood sugarcane can withstand, and how much and for how long the water table needs to be lowered before flooding can resume without reducing yields. Concurrently, microbiological studies should determine water tables, flood durations, temperature conditions, and other environmental variables in which oxidation of organic soils would not occur.

- **Conduct long-term studies to improve water tolerance of commercial sugarcane cultivars in Florida.**

Past research suggests that a concentrated genetic program to improve water tolerance of sugarcane should be successful. Sugarcane already identified in India as flood tolerant, and commercial type cultivars identified above would be used as beginning genetic material. Both classical and molecular genetics approaches are recommended.

- **Conduct agronomic studies to extend flood duration of rice grown in EAA.**

Rice growers in other areas plant by airplane directly on flooded fields and have developed special equipment to harvest on flooded fields. Efforts to successfully achieve these two practices for commercial rice production in the EAA would help extend flood duration and thereby reduce subsidence.

- **Conduct ecological investigations to determine if new management strategies to control subsidence can also be used to improve habitat in the EAA for endangered species.**

- **Determine on-farm hydrologic conditions necessary to manage for high crop yields while controlling subsidence.**

- **Determine changes to C&SF Project necessary to support farmers' intent to manage their cropping systems while controlling subsidence.**

- **Evaluate effect of managing water table for zero-subsidence agriculture on:**

  - Conveyance of water from Lake Okeechobee to natural areas downstream from EAA.
  - Hydropatterns in natural areas downstream of EAA.
  - Water flow to Florida Bay.
  - Long- and short-term export of P from EAA to natural areas downstream.

OPPORTUNITIES FOR COOPERATION

Three public institutions with scientists in place in or near the EAA are the: 1) SFWMD, 2) IFAS-EREC in Belle Glade, and 3) USDA-ARS Sugarcane Field Station in Canal Point. Public science projects on agricultural production systems in the EAA are conducted primarily by the IFAS-EREC and USDA-ARS. The SFWMD supports projects that are more hydrological than agricultural. Much hydrological work is in progress and proposed in the EAA by IFAS, SFWMD, and consultants.

Several private agricultural companies also have research departments and full-time scientists working on ecosystem-related issues, and several scientists have worked as consultants on these issues. Technical assistance from public institutions comes primarily from the Cooperative Extension Service, USDA-NRCS, and Palm Beach Soil and Water Conservation District.

The FSCL is also involved in several scientific initiatives related to sugarcane. The FSCL has a long history of funding agricultural science projects related to sugarcane in the EAA and has developed a process of requesting proposals from EAA scientists. These proposals are examined by a committee of managers and scientists from companies that comprise the League and other companies who support the League's science efforts.

The EPD is a self-imposed taxing district formed by EAA growers, which has the power to assess its members a tax of $12.35 per ha. Among its purposes are to conduct scientific research on environmental-agricultural matters. The EPD currently funds studies being done in the EAA and WCAs by the UF and Duke University Center for Wetland Research.

All the agricultural-hydrological-ecological science is interrelated, but much of the necessary interaction among SFWMD, ARS, NRCS, IFAS, FSCL, and private company scientists has been lacking. An extremely useful function for the Science Subgroup would be to form a committee that would unite all of the efforts. This could serve to help scientists and managers from all institutions remain aware of all work and directions in progress and proposed.

The Science Subgroup should also organize at least one meeting per year at which all funded scientists involved in the effort would be required to present their annual accomplishments. This would serve to keep all administrators and scientists aware of work in progress and would help uncover areas where interdisciplinary efforts or communication could facilitate scientific efforts.

ACKNOWLEDGMENTS

Appreciation is extended to the many sources who aided preparation of this chapter. Some of these persons were D.L. Anderson, H.J. Andreis, E. Arias, J.A. Browder, G.R. Burns, C.E. Carter, R.H. Cherry, F.J. Coale, J.C. Comstock, C.W. Deren, J.W. Dunckelman, B.R. Eiland, Nael El-Hout, E. Flaig, G.J. Gascho, D.G. Hall, F.T. Izuno, D.B Jones, J.D. Miller, R. Perdomo, P.S. Porter, K.R. Reddy, P. Rosendahl, C.A. Sanchez, T.J. Schueneman, J.M. Shine Jr., G.H. Snyder, O. Sosa Jr., D. Swift, P.Y.P. Tai, M.F. Ulloa, D. Unsell, P. Whalen, and all participants in the April 1994 phosphorus workshop.

BIBLIOGRAPHY

Abtew, W., and N. Khanal. 1993. Water budget analysis for the Everglades Agricultural Area - an organic soil drainage basin. SFWMD, West Palm Beach, Florida.

Allison, R.V. 1956. The influence of drainage and cultivation on subsidence of organic soils under conditions of Everglades reclamation. Soil and Crop Science Society of Florida Proceedings 16:21-31.

Alvarez, J., G.H. Snyder, and D.B. Jones. 1989. The integrated program approach in the development of the Florida rice industry. Journal of Agronomic Education 18:6-11.

Anderson, D.L. 1989. A review: soils, nutrition, and fertility practices of the Florida sugarcane industry. Soil and Crop Science Society of Florida Proceedings 49:78-87.

Anderson, D.L., E.A. Hanlon, A.B. Bottcher, and A. Ceric. 1994. Phosphorous in drainage waters from organic soils (Histosols) of Florida. Circular SSLAG-1. UF, Gainesville, Florida.

Anderson, D.L., and M.D. Howell. 1993. Implementation of the Everglades Surface Water Improvement and Management Plan in the EAA. Sugar Journal 56(6):5-10.

Anderson, D.L., D.B. Jones, and G.H. Snyder. 1987. Response of a rice-sugarcane rotation to calcium silicate slag on Everglades Histosols. Agronomy Journal 79:521-535.

Andreis, H.J. 1975. Macro and micro nutrient content of millable Florida sugar cane. Sugar Journal 37(8):10-12.

Andreis, H.J. 1976. A water table study on an Everglades peat soil: Effects on sugarcane and on soil subsidence. Sugar Journal 39(6):8-12.

Bellamy, J. 1948. Taming the Everglades, a report on water control. Miami Herald pamphlet.

Bohn, H.L., B.L. McNeal, and G.A. O'Connor. 1985. Soil chemistry. John Wiley & Sons, New York.

Broadbent, F.E. 1960. Factors influencing the decomposition of organic soils of the California Delta. Hilgardia 29:587-612.

Brooks, J.E., and E.F. Lowe. 1984. U.E. EPA clean lakes program, phase I. Diagnostic-feasibility study of the Upper St. Johns River Chain of Lakes. Volume II - feasibility study. Technical Publication SJ 84-15. SJRWMD, Palatka, Florida.

Browder, J.A., and B.G. Volk. 1978. Systems model of carbon transformations in soil subsidence. Ecological Modelling 5:269-292.

Brown, K. 1994. Babbitt supports canal projects. The Palm Beach Post. January 16, 1994, pp. 1A, 21A.

Burgess, D. 1991. Floods convince growers to plant more Q117 and Q120. Bureau of Sugar Experiment Stations (Australia) Bulletin No. 34:14-15.

Canfield, D.E. Jr., and M.V. Hoyer. 1988. The eutrophication of Lake Okeechobee. Lake and Reservoir Management 4(2):91-99.

Carter, C.E. 1980. Redox potential and sugarcane yield relationship. Transactions of the ASAE 23:924-927.

Carter, C.E. 1986. Oxidation reduction due to a high water table. Proceedings of International Seminar on Land Drainage. Helsinki University of Technology, Helsinki, Finland.

Carter, C.E., R.L. Bengston, C.R. Camp, J.L. Fouss, and J.S. Rogers. 1992. Crop yield increases required to justify subsurface drainage installation costs in the lower Mississippi Valley. Pages 428-439 *in* Sixth National Drainage Symposium. ASAE.

Carter, C.E., R.L. Bengston, and J.S. Rogers. 1988a. Drainage needs as indicated by high water tables. Transactions of the ASAE 31:1410-1415.

Carter, C.E., and C.R. Camp. 1983. Subsurface drainage of an alluvial soil increased sugarcane yields. Transactions of the ASAE 26:426-429.

Carter, C.E., C.B. Elkins, and J.M. Floyd. 1970. Water management in sugarcane production. Proceedings American Society of Sugar Cane Technologists 17:10-24.

Carter, C.E., and J.M. Floyd. 1970. Effects of water table depths on sugarcane yields in Louisiana. Proceedings American Society of Sugar Cane Technologists 1:5-7.

Carter, C.E., and J.M. Floyd. 1975. Inhibition of sugarcane yields by high water table during dormant season. Proceedings American Society of Sugar Cane Technologists 4:14-18.

Carter, C.E., J.L. Fouss, and V. McDaniel. 1988b. Water management increases sugarcane yields. Transactions of the ASAE 31:503-507.

CH2M Hill, Inc. 1979. Phase 3 water quality studies in the Everglades Agricultural Area of Florida. Report submitted to the FSCL, Clewiston, Florida.

Cherry, R.H. 1984. Flooding to control the grub *Ligyrus subtropicus* (Coleoptera: Scarabaeidae) in Florida sugarcane. Journal of Economic Entomology 77:254-257.

Cherry, R.H., D.B. Jones, and F.W. Mead. 1986. Leafhoppers (Homoptera: Cicadellidae) and planthoppers (Homoptera: Delphacidae) in Southern Florida rice fields. Florida Entomologist 69:180-184.

Cisar, J.L., J.L. Haydu, and L.B. McCarty. 1994. Sod production in the EAA. *In* A.B. Bottcher and F.T. Izuno, editors. Everglades Agricultural Area (EAA): Water, Soil, Crop, and Environmental Management. University Press of Florida, Gainesville, Florida.

Clayton, B.S., J.R. Neller, and R.V. Allison. 1942. Water control in the peat and muck soils of the Florida Everglades. Bulletin 378. Agricultural Experiment Station, UF, Gainesville, Florida.

Coale, F.J., and C.W. Deren. 1992. Impact of elevated field water table on sugarcane productivity. Proposal to the FSCL, Inc.

Coale, F.J., F.T. Izuno, and A.B. Bottcher. 1994a. Sugarcane production impact on nitrogen and phosphorous in drainage water from an Everglades Histosol. Journal of Environmental Quality 23:116-120.

Coale, F.J., F.T. Izuno, and A.B. Bottcher. 1994b. Phosphorous in drainage water from sugarcane in the Everglades Agricultural Area as affected by drainage rate. Journal of Environmental Quality 23:121-126.

Coale, F.J., D.B. Jones, and T.J. Schueneman. 1992. Rice industry growing, variety census shows. Florida Grower & Rancher 86(1):28.

Coale, F.J., C.A. Sanchez, F.T. Izuno, and A.B. Bottcher. 1993. Nutrient accumulation and removal by sugarcane grown on Everglades Histosols. Agronomy Journal 85:310-315.

Collins, M.E., G.W. Schellentrager, J.A. Doolittle, and S.F. Shih. 1986. Using ground-penetrating radar to study changes in soil map unit composition in selected Histosols. Soil Science Society of America Journal 50:408-411.

Cooper, R.M. 1989. An atlas of the Everglades Agricultural Area surface water management basins. Technical Memorandum DRE-274. SFWMD, West Palm Beach, Florida.

Cox, S., D. Lewis, S. McCollum, M. Bledsoe, and R. Marrotte. 1988. Subsidence study of the Everglades Agricultural Area. USDA, SCS, Greenacres, Florida, and SFWMD, West Palm Beach, Florida.

Datnoff, L.E., R.N. Raid, C.A. Sanchez, and M.L. Sommerfeld. 1992. Influence of vesicular-arbuscular mycorrhizae on celery seedling growth and development. Phytophathology 82:1170.

Datnoff, L.E., R.N. Raid, B.T. Scully, and P.S. Porter. 1991. Use of mycorrhizae fungi for reduction of phosphorous inputs in celery production. Proposal to the SFWMD, West Palm Beach, Florida.

Datnoff, L.E., G.H. Snyder, and C.W. Deren. 1992. Influence of silicon fertilizer grades on blast and brown spot development and on rice yields. Plant Disease 76:1011-1013.

Deren, C.W. 1990. Evaluation of flood-tolerance in sugarcane. Proposal to Center of Natural Resources.

Deren, C.W. 1991a. Evaluation of flood-tolerance in sugarcane. Proposal submitted to the Western Palm Beach Farm Bureau.

Deren, C.W. 1991b. Breeding and selection for flood tolerance in sugarcane. Proposal to FSCL, Inc.

Deren, C.W., L.E. Datnoff, and G.H. Snyder. 1992. Variable silicon content of rice cultivars grown on Everglades Histosols. Journal of Plant Nutrition 15:2363-2368.

Deren, C.W., G.H. Snyder, and J.D. Miller. 1989. Breeding and selection of flood-tolerant sugarcane for Florida and the Caribbean. CBAG grant pre-proposal.

Deren, C.W., G.H. Snyder, and J.D. Miller. 1991a. Breeding and genetics of flood-tolerant sugarcane. Preliminary proposal to EPD.

Deren, C.W., G.H. Snyder, and J.D. Miller. 1991b. Anatomy, physiology, and morphology of flood-tolerant clones in the *Saccharum* complex. Preliminary proposal to EPD.

Deren, C.W., G.H. Snyder, and J.D. Miller. 1991c. Sugarcane flooding sequence, duration, and depth. Preliminary proposal to EPD.

Deren, C.W., G.H. Snyder, J.D. Miller, and P.S. Porter. 1989. Wetland agriculture: multidisciplinary development of a low-input sustainable agriculture system to serve as a model for disturbed wetlands of the Southeast. LISA grant proposal.

Deren, C.W., G.H. Snyder, J.D. Miller and P.S. Porter. 1991. Screening for heritability of flood-tolerance in the Florida (CP) sugarcane breeding population. Euphytica 56:155-160.

Diaz, O.A., D.L. Anderson, and E.A. Hanlon. 1993. Phosphorous mineralization from Histosols of the Everglades Agricultural Area. Soil Science 156:178-185.

Duxbury, J.M., and R.L. Tate III. 1981. The effect of soil depth and crop cover on enzymatic activities in Pahokee muck. Soil Science Society of America Journal 45:322-328.

Elliot, C.L., and G.H. Snyder. 1986. A field test for identifying low-Fe Histosols associated with rice seedling chlorosis. Soil and Crop Science Society of Florida Proceedings 46:91-93.

Elliot, C.L., G.H. Snyder, and D.B. Jones. 1988. Rapid gravimetric determination of Si in rice straw. Communications in Soil Science and Plant Analysis 19:1543-1550.

Fennema, R.J., C.J. Neidrauer, R.A. Johnson, W.A. Perkins, and T.K. MacVicar. 1994. A computer model to simulate natural Everglades hydrology. Pages 249-289 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Florida Sugar Cane League (FSCL). 1978. Water quality studies in the Everglades Agricultural Area of Florida.

Foster, R.E., R.H. Cherry, and D.B. Jones. 1989. Spatial distribution of the rice stink bug (Heteroptera: Pentatomidae) in Florida rice. Journal of Economic Entomology 82:507-509.

Gascho, G.J. 1985. Water-sugarcane relationships. Sugar Journal 48(6):11-17.

Gascho, G.J., and S.F. Shih. 1979. Varietal response of sugarcane to water table depth. 1. Lysimeter performance and plant response. Soil and Crop Science Society of Florida Proceedings 38:23-27.

Genung, W.G. 1970. Flooding experiments for control of wireworms attacking vegetable crops in the Everglades. Florida Entomologist 53(2):55-63.

Germain, G.J., and J.E. Shaw. 1988. Surface water quality monitoring network. Tech. Pub. 88-3. SFWMD, West Palm Beach, Florida.

Gifford, B. 1994. The government mucked up the Everglades. The Palm Beach Post. January 16, 1994, pp. 1F, 5F.

Gill, B.S., J.D. Miller, P.Y.P. Tai, G. Kidder, G.J. Gascho, and S.F. Shih. 1979. Organic soil conservation: screening of sugarcane germplasm adapted to wetland culture. Project proposal.

Glaz, B. 1994. Sugar cane variety census: Florida 1993. Sugar y Azucar 88(1):39-44.

Glaz, B., and M.S. Kang. 1985. Preliminary analysis of sugarcane clone response to water-table level on organic soil. Inter-American Sugar Cane Seminars: Irrigation and Drainage. Paper no. 27.

Glaz, B., and M.F. Ulloa. 1993. Fallow and successive planting of sugarcane in Florida. Sugar y Azucar 88(6):42 (abstract).

Glaz, B., and M.F. Ulloa. 1994. Sugarcane in monoculture or in rotation with sweet corn. Field Crops Research 36:167-173.

Glaz, B., M.F. Ulloa, and R. Parrado. 1989. Cultivation, cultivar, and crop age effects on sugarcane. Agronomy Journal 81:163-167.

Glinsmann, W.H., H. Irausquin, and Y.K. Park. 1986. Evaluation of health aspects of sugars contained in carbohydrate sweeteners. Report from FDA's Sugars Task Force, 1986.

Haberen, J. 1994. Agronomy and the environment: building the gap. Agronomy News 1994 (April):10-11.

Hall, D.G. 1981. A biological-chemical IPM program for the sugarcane borer. Proceedings Inter-American Sugar Cane Seminar - Insect and Rodent Pests 2:89-95.

Hall, D.G. 1990. Stand and yield losses in sugarcane caused by the wireworm *Melanotus communis* infesting plant cane in Florida. Florida Entomologist 73:298-302.

Hall, D.G., and F.D. Bennett. 1994. Biological control and IPM of sugarcane pests in Florida. *In* Rosen, Capinera, and Bennett, editors. Biological Control - A Florida Perspective. Intercept Ltd., Andover, Hampshire, United Kingdom.

Hall, D.G., and R.H. Cherry. 1993. Effect of temperature in flooding to control the wireworm *Melanotus communis* (Coleoptera:Elateridae). Florida Entomologist 76(1):155-160.

Havens, K.E., and A.D. Steinman. 1995. Aquatic systems. Pages 121-151 *in* J.E. Rechcigl, editor. Soil Amendments: Impacts on Biotic Systems. Lewis Publishers, Boca Raton, Florida.

Hebert, L.P. 1967. Florida sugar cane variety census for 1966. Sugar Journal 29(8):24-26.

Hortenstine, C.C., and R.B. Forbes. 1972. Concentrations of nitrogen, phosphorous, potassium, and total soluble salts in soil solution samples from fertilized and unfertilized Histosols. Journal of Environmental Quality 1:446.

Izuno, F.T., and A.B. Bottcher. 1987. Final report: The effects of on-farm agricultural practices in the organic soils of the Everglades Agricultural Area on nitrogen and phosphorus transport. Part II. Components of the EAA agricultural system that relate to water quality in south Florida. IFAS, UF, Gainesville, Florida.

Izuno, F.T., A.B. Bottcher, L.T. Capone, W.A. Davis, R.M. Garcia, C.F. Miller, R.W. Rice, and J.D. Stuck. 1993. Implementation and verification of BMPs for reducing phosphorus loading in the EAA. Phase II: Final report submitted to the Everglades Agricultural Area Environmental Protection District. EREC, IFAS, UF.

Izuno, F.T., D. Bottcher, F.J. Coale, C.A. Sanchez, D.B. Jones, C.W. Deren, and J. Alvarez. 1990. Verification and implementation of BMPs for reducing phosphorus loading in the EAA. Proposal submitted to the FSCL.

Izuno, F.T., A.B. Bottcher, F.J. Coale, W.A. Davis, D.B. Jones, C.F. Miller, M. Omary, K.R. Reddy, C.A. Sanchez, and L.A. Taylor. 1991a. The effects of on-farm agricultural practices in the organic soils of the EAA on nitrogen and phosphorous transport: screening BMP's for phosphorous loading and concentration reductions. Final report (draft). IFAS, UF.

Izuno, F.T., C.A. Sanchez, F.J. Coale, A.B. Bottcher, and D.B. Jones. 1991b. Phosphorous concentrations in drainage water in the Everglades Agricultural Area. Journal of Environmental Quality 20:608-619.

Johnson, L. 1974. Beyond the Fourth Generation. University Press of Florida, Gainesville, Florida. 230 pp.

Jones, D.B. 1993. Rice ratoon response to main crop harvest cutting height. Agronomy Journal 85:1139-1142.

Jones, D.B., and R.H. Cherry. 1986. Species composition and seasonal abundance of stink bugs (Heteroptera: Pentatomidae) in southern Florida rice. Journal of Economic Entomology 79:1226-1229.

Jones, D.B., and G.H. Snyder. 1987. Seeding rate and row spacing effects on yield and yield components of ratoon rice. Agronomy Journal 79:627-629.

Jones, D.B., G.H. Snyder, and J. Alvarez. In Press. Rice and other aquatic crops. *In* A.B. Bottcher and F.T. Izuno, editors. Everglades Agricultural Area (EAA): Water, Soil, Crop, and Environmental Management. University Press of Florida, Gainesville, Florida.

Jones, L.A. 1948. Soils, geology and water control in the Everglades region. USDA-SCS, UF Agricultural Experiment Station, Gainesville, Florida. 168 pp.

Kang. M.S., G.H. Snyder, and J.D. Miller. 1986. Evaluation of *Saccharum* and related germplasm for tolerance to high water table on organic soil. Journal American Society of Sugar Cane Technologists 6:59-63.

Kenworthy, T. 1994. Administration plan for Everglades leaves activists, business dissatisfied. The Washington Post, January 16, 1994, p. 8A.

Kidder, G., S.F. Shih, P. Lyrene and G.J. Gascho. Prior to 1978. Water control for sugarcane. A project proposal.

LeCroy, W.C., and J.R. Orsenigo. 1964. Sugarcane culture in the Florida Everglades. Soil and Crop Science Society of Florida Proceedings 24:437-441.

Levanon, D., and I. Levin. 1984. Preservation of peat soil by cultivation of perennial herbage crops. Pages 529-535 *in* Land Subsidence. IAHS Publication 151. Venice, Italy.

LOTAC I. 1986. Final report of the Lake Okeechobee Technical Advisory Committee. Submitted to the FDER, Tallahassee, Florida.

LOTAC II. 1990. Final report of the Lake Okeechobee Technical Advisory Council. Submitted to the Governor of the State of Florida, Secretary of the FDER, and Governing Board of the SFWMD, Tallahassee, Florida.

Lowe, E.F. 1983. Distribution and structure of floodplain plant communities in the upper basin of the St. Johns River, Florida. Technical Publication SJ 83-8, SJRWMD, Palatka, Florida.

Lucas, R.E. 1982. Organic soils (Histosols): formation, distribution, physical and chemical properties, and management for crop production. Michigan State University Agricultural Experiment Station Research Report 435. East Lansing, Michigan.

Maceina, M.J., and D.M. Soballe. 1990. Wind-related limnological variation in Lake Okeechobee, Florida. Lake and Reservoir Management 6(1):93-100.

McCollum, S.H., O.E. Cruz, L.T. Stem, W.H. Wittstruck, R.D. Ford, and F.C. Wahs. 1978. Soil survey of Palm Beach County area, Florida. USDA, SCS.

McDowell, L.L., J.C. Stephens, and E.M. Stewart. 1969. Radiocarbon chronology of the Florida Everglades peat. Soil Science Society of America Proceedings 33:743-745.

Miller, C.F. 1918. Inorganic composition of a peat and of the plant from which it was formed. Journal of Agricultural Research 13:605-609.

Morris, T. 1975. Everglades Agricultural Area backpumping study. Pages 346-419 *in* F.G. Nordie and T. Gayle, editors. Water Quality Models for Understanding Potential Eutrophication in Lake Okeechobee, Florida. Center for Wetlands, UF, Gainesville, Florida.

Mowry, H., and H.H. Bennett. 1948. Soils, geology, and water control in the Everglades region. Bulletin 442. Agricultural Experiment Station, UF, Gainesville, Florida.

Naidu, K.M., and S. Arulraj. 1992. Evaluation for waterlogging resistance. *In* Research Highlights 1991-92. The Seshan Printers, Coimbatore.

Negi, O.P., S.P. Naithani, and S. Poddar. 1971. Root studies of outstanding sugarcane varieties of Bihar, India. Pages 733-788 *in* M.T. Henderson, editor. Proceedings of the International Society of Sugar Cane Technologists Fourteenth Congress. Franklin Press, Baton Rouge, Louisiana.

Neller, J.R. 1944. Oxidation loss of Lowmoor peat in fields with different water tables. Soil Science 58:195-204.

Nicholson, K. 1983. Partitioning of phosphorous in a Florida Histosol. Ph.D. Dissertation. UF, Gainesville, Florida.

Nuessly, G.S., C.A. Sanchez, F.T. Izuno, G.H. Snyder, J.A. Dusky, C.W. Deren, R.N. Raid, and P.S. Porter. 1990. Studies to reduce the input of and determine fate of agrichemicals in target and non-target systems. Proposal to National Science Foundation.

Patrick, W.H. Jr., R.H. Gambrell, P. Parkplan, and T. Fang. 1994. Mercury in soils and plants in the Florida Everglades sugarcane area. *In* C.J. Watras and J.W. Huckabee, editors. Mercury Pollution: Integration and Synthesis. Papers presented at the International Conference on Mercury as a Global Pollutant, June 1992, Monterey, California. Lewis Publishers, Boca Raton, Florida.

Porter, P.S., G.H. Snyder, and C.W. Deren. 1991. Flood-tolerant crops for low input sustainable agriculture in the Everglades Agricultural Area. Journal of Sustainable Agriculture 2:77-101.

Rahi, G.S., and S.F. Shih. 1979. Soil-water characteristics of Histosols as related to water table depth. Soil and Crop Science Society of Florida Proceedings 39:34-37.

Reddy, K.R. 1983. Soluble phosphorous release from organic soils. Agriculture, Ecosystems and Environment 9:373-382.

Reddy, K.R. 1987. The effect of flooding on physical, chemical, and microbiological properties of Histosols. *In* G.H. Snyder, editor. Agricultural Flooding of Organic Soils. Agricultural Experiment Station, IFAS, UF, Gainesville, Florida.

Reddy, K.R., K.L. Campbell, D.A. Graetz, and K.M. Portier. 1982. Use of biological filters for treating agricultural drainage effluents. Journal of Environmental Quality 11:591-595

Reddy, K.R., R.D. DeLaune, W.F. DeBusk, and M.S. Koch. 1993. Long-term nutrient accumulation rates in the Everglades. Soil Science Society of America Journal 57:1147-1155.

Reddy, K.R., and D.A. Graetz. 1981. Use of shallow reservoir and flooded organic soil systems for waste water treatment: nitrogen and phosphorous transformations. Journal of Environmental Quality 10:113-119.

Reddy, K.R., and P.S.C. Rao. 1983. Nitrogen and phosphorous fluxes from a flooded organic soil. Soil Science 136:300-307.

Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas Jr., and P.E. Rasmussen. 1995. Soil organic matter changes resulting from tillage and biomass production. Journal of Soil and Water Conservation 50:253-261.

Roach, B.T., and R.T. Mullins. 1985. Testing sugarcane for waterlogging tolerance. Proceedings Australian Society of Sugar Cane Technologists 95:101.

Sanchez, C.A. 1990. Soil-testing and fertilization recommendations for crop production on organic soils in Florida. Bulletin 876 (Technical). Agricultural Experiment Station, UF, Gainesville, Florida.

Sanchez, C.A., and P.S. Porter. 1987. Phosphorous in the organic soils of the Everglades Agricultural Area. *In* F.T. Izuno and A.B. Bottcher, editors. The Components of the Everglades Agricultural System that Relate to Water Quality in South Florida. Annual report to the SFWMD Project "The effect of on-farm agricultural practices in the organic soils of the EAA on nitrogen and phosphorous transport."

Scheidt, D.J. 1989. Pesticides and Everglades National Park: South Florida use and threat. Pages 365-375 *in* D.W. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Scheidt, D.J., M.D. Flora, and D.R. Walker. 1989. Water quality management for Everglades National Park. Pages 377-390 *in* D.W. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Schueneman, T.J., and C.A. Sanchez. 1994. Vegetable production in the EAA. *In* A.B. Bottcher and F.T. Izuno, editors. Everglades Agricultural Area: Water, Soil, Crop, and Environmental Management. University Press of Florida, Gainesville, Florida.

Science Sub-Group. 1993. Federal objectives for the South Florida restoration. Science Sub-Group of the South Florida Management and Coordination Working Group.

Shih, S.F., and J.A. Doolittle. 1984. Using radar to investigate organic soil thickness in the Florida Everglades. Soil Science Society of America Journal 48:651-656.

Shih, S.F., J.W. Mishoe, J.W. Jones, and D.L. Myhre. 1977a. Modelling the subsidence of Everglades organic soil. Paper No. 77-2034, ASAE 1977 Annual Meeting, St. Joseph, Michigan.

Shih, S.F., J.W. Mishoe, J.W. Jones, and D.L. Myhre. 1977b. Subsidence related to land use in Everglades Agricultural Area. Paper No. 77-5022, ASAE 1977 Annual Meeting, St. Joseph, Michigan.

Shih, S.F., J.W. Mishoe, J.W. Jones, and D.L. Myhre. 1979. Subsidence related to land use in Everglades Agricultural Area. Transactions of the ASAE 22(3):560-568.

Shih, S.F., G.S. Rahi, and D.S. Harrison. 1982. Evapotranspiration studies on rice in relation to water use efficiency. Transactions of the ASAE 25:702-712.

Shih, S.F., G.S. Rahi, G.H. Snyder, D.S. Harrison, and A.G. Smajstrla. 1983. Rice yield, biomass, and leaf area related to evapotranspiration. Transactions of the ASAE 26:1458-1464.

Shih, S.F., E.H. Stewart, J.L.H. Allen, and J.W. Hilliard. 1979. Variability of depth to bedrock in Everglades organic soil. Soil and Crop Science of Florida 38:66-71.

Shih, S.F., D.E. Vandergrift, D.L. Myhre, G.S. Rahi, and D.S. Harrison. 1981. The effect of land forming on subsidence in the Florida Everglades organic soil. Soil Science Society of America Journal 45:1206-1209.

Simons, J.N. 1991. Mercury in the Everglades: What is the role of agriculture? Florida Naturalist 64(1):7-9.

Sincock, J.L. 1958. Waterfowl ecology in the St. Johns River Valley as related to the proposed conservation areas and changes in the hydrology from Lake Harney to Fort Pierce, Florida. FGFWFC, Tallahassee, Florida.

Smith, G. 1990. The Everglades Agricultural Area revisited. Citrus and Vegetable Magazine 53(9):40-42.

Snyder, G.H., editor. 1987. Agricultural flooding of organic soils. Technical Bulletin 870. Agricultural Experiment Station, UF, Gainesville, Florida.

Snyder, G.H. 1994. Soils of the EAA. *In* A.B. Bottcher and F.T. Izuno, editors. Everglades Agricultural Area (EAA): Water, Soil, Crop, and Environmental Management. University Press of Florida, Gainesville, Florida.

Snyder, G.H., H.W. Burdine, J.R. Crockett, G.J. Gascho, D.S. Harrison, G. Kidder, J.W. Mishoe, D.L. Myhre, F.M. Pate, and S.F. Shih. 1978. Water table management for organic soil conservation and crop production in the Florida Everglades. Technical Bulletin 801. Agricultural Experiment Station, UF, Gainesville, Florida.

Snyder, G.H., and J.M. Davidson. 1994. Everglades agriculture, past, present, and future. Pages 85-115 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Snyder, G.H., and D.B. Jones. 1988a. Phosphorous and potassium fertilization of rice on Everglades Histosols. Soil and Crop Science Society of Florida 48:22-25.

Snyder, G.H., and D.B. Jones. 1988b. Prediction and prevention of Iron-related rice seedling chlorosis on Everglades Histosols. Soil Science Society of America Journal 52:1043-1046.

Snyder, G.H., and D.B. Jones. 1992. Phosphorous and potassium fertilization of rice - 1991 studies. *In* F.J. Coale, editor. 1992 Rice Growers Seminar, Belle Glade EREC Research Report EV-1992-1.

Snyder, G.H., R.H. Carruthers, J. Alvarez, and D.B. Jones. 1986a. Sugarcane production in the Everglades following rice. Journal of the American Society of Sugarcane Technologists 6:50-55.

Snyder, G.H., D.B. Jones, and G.J. Gascho. 1986b. Silicon fertilization of rice on Everglades Histosols. Soil Science Society of America Journal 50:1259-1263.

Soil Conservation Service. 1981. Agricultural Handbook 296: Land resource regions and major land resource areas of the United States. USDA, Washington, D.C.

Sorenson, L.H. 1974. Rate of decomposition of organic matter in soils as influenced by repeated air drying-rewetting and repeated additions of organic matter. Soil Biology and Biochemistry 6:287-292.

South Florida Water Management District. 1992a. Chapter 40E-63, Florida annotated code. Everglades Agricultural Area Regulatory Program. SFWMD Rules, West Palm Beach, Florida.

South Florida Water Management District. 1992b. Surface Water Improvement and Management Plan for the Everglades, Supporting Information Document. SFWMD, West Palm Beach, Florida.

Stephens, J.C. 1984. Subsidence of organic soils in the Florida Everglades: a review and update. Pages 375-384 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Stephens, J.C., L.H. Allen Jr., and E.C. Chen. 1984. Organic soil subsidence. Geological Society of America, Reviews in Engineering Geology 6:107-122.

Stephens, J.C., and L. Johnson. 1951. Subsidence of organic soils in the upper Everglades region of Florida. Soil Science Society of Florida Proceedings 11:191-237.

Stephens, J.C., and W.H. Speir. 1969. Subsidence of organic soils in the U.S.A. International Association of Scientific Hydrology (Tokyo) Publication No. 89:523-534.

Stevens, F.D. 1948. Experience with flooded cane under Everglades conditions. Sugar Journal 11(1):3-4.

Stone, J.A., and D.E. Legg. 1992. Agriculture and the Everglades. Journal of Soil and Water Conservation, May-June:207-215.

Tate, R.L. III. 1976. Nitrification in Everglades Histosols: a potential role in soil subsidence. Pages 657-663 *in* Proceedings of 2nd International Symposium on Land Subsidence, Anaheim, California. Publication 121, International Association of Hydrological Sciences.

Tate, R.L. III. 1979a. Microbial activity in organic soils affected by soil depth and crop. Applied and Environmental Microbiology 37:1085-1090.

Tate, R.L. III. 1979b. Effect of flooding on microbial activities in organic soil: carbon metabolism. Soil Science 128:267-273.

Tate, R.L. III. 1980a. Effect of several environmental parameters on carbon metabolism in Histosols. Microbiological Ecology 5:329-336.

Tate, R.L. III. 1980b. Microbial oxidation of organic matter of Histosols. Advances in Microbial Ecology 4:169-201.

Terry, R.E. 1980. Nitrogen mineralization in Florida Histosols. Soil Science Society of America Journal 44:747-750.

Terry, R.E., and R.L. Tate III. 1980. Denitrification as a pathway for nitrate removal from organic soils. Soil Science 129(3):162-166.

U.S. Department of Agriculture. 1994. National Research Initiative Competitive Grants Program, Part 1. USDA, Washington, D.C.

Volk, B.G. 1973. Everglades Histosol subsidence: 1. CO_2 evolution as affected by soil type, temperature, and moisture. Soil and Crop Science Society of Florida Proceedings 32:132-135.

Whalen, P.J., J. VanArman, J. Mulliken, D. Swift, S. Bellmund, D. Worth, T.D. Fontaine, L. Gulick, and S. Formati. 1992. Draft Surface Water Improvement and Management Plan for the Everglades. SFWMD, West Palm Beach, Florida.

Yadav, R.L., and S.R. Prasad. 1992. Conserving the organic matter content of the soil to sustain sugarcane yield. Experimental Agriculture 28:57-62.

Zaffke, M. 1983. Plant communities of Water Conservation Area 3A: base-line documentation prior to the operation of S-339 and S-340. Technical Memorandum. SFWMD, West Palm Beach, Florida.

Zelazny, L.W., and W.H. Carlisle. 1974. Physical, chemical, elemental and oxygen-containing functional group analysis of selected Florida Histosols. Pages 63-78 (Chapter 6) *in* Histosols. Special Publication No. 6, Soil Science Society of America, Madison, Wisconsin.

APPENDIX A

List of Attendees at April 14, 1994, Phosphorus Workshop

David L.	Anderson	University of Florida EREC
Henry	Andreis	United States Sugar Corp.
Velton	Banks	FSCL, Inc.
Del	Bottcher	Soil & Water Eng. Tech.
Joan	Browder	U.S. DOC-NOAA/NMFS, Miami, Florida
Gary	Buckingham	USDA-ARS, Gainesville, Florida
George R.	Burns	USDA-ARS, Athens, Georgia
Laurene	Capone	University of Florida EREC
Lawrence	Datnoff	University of Florida EREC
C.W.	Deren	University of Florida EREC
Barney	Eiland	Okeelanta
Nael	El-Hout	South Bay Growers, Inc.
Barry	Glaz	USDA-ARS, Canal Point, Florida
Forrest T.	Izuno	University of Florida EREC
Gaspar	Korndorfer	University of Florida EREC
Ken	Liudahl	USDA-SCS, West Palm Beach, Florida
J.D.	Miller	USDA-ARS, Canal Point, Florida
Russell	Nagata	University of Florida EREC
Bill	Orem	USGS
Ramesh	Reddy	University of Florida, Gainesville
Ron	Rice	University of Florida EREC
Fernando	Sanchez	Sugar Farms Co-op
Lewis	Schoolfield	FSCL, Inc.
Jim	Shine	FSCL, Inc.
George H.	Snyder	University of Florida EREC
James D.	Stuck	University of Florida, Gainesville
Modesto F.	Ulloa	Sugar Farms Co-op
Henro	Van Dohkum	University of Florida EREC
Cees Jan	Vermulst	University of Florida EREC

APPENDIX B

Soil Sediment Characterization in the Everglades Agricultural Area: Relevant Literature.

Dr. David L. Anderson was requested to prepare a literature review for seven subject categories related to phosphorus issues in the EAA. He submitted the following thorough review.

Subject Categories:

1) EAA Water Quality
2) Lake Okeechobee Water Quality
3) EAA Sediments
4) Lake Okeechobee Sediments
5) Soils
6) Plans, Implementations, Measurements
7) Dutch Sediments

1,3,6 Adey, W., C. Luckett, and F. Jensen. 1992. Phosphorus removal from Everglades Agricultural Area (EAA) canals using controlled algae production.

2,4 Anderson, D.L. 1990. Biochemical behavior and transport of phosphorus in the Lake Okeechobee basin, field verification and demonstration studies. Final Report, Task 1.4.3. West Palm Beach, Fl.: SFWMD.

1,2,3,4 Anderson, D.L. 1992. Introduction and program description for reduction of phosphorus concentrations in agricultural drainage by precipitation, coagulation, and sedimentation. FSCL. Presented to SFWMD, SAGE Committee, May 18. 46 pp.

5 Anderson, D.L. and R.B. Beverly. 1985. The effects of drying upon extractable P, K, and bulk density of organic soils in the Everglades. Soil Sci. Soc. Am. J. 49:362-366.

2,4 Anderson, D.L. and A. Faber. 1989. Biochemical behavior and transport of phosphorus in the Lake Okeechobee basin, effect of soil amendments on P retention capacity. Final Report, Task 1.4.1. West Palm Beach, Fl.: SFWMD. 128 pp.

1,3 Anderson, D.L., E.A. Hanlon, A.B. Blottcher and E. Claric. 1994. Phosphorus in drainage waters from organic soils (Histosols) in Florida. University of Florida IFAS, SSLAH-1. 3 pp.

6,1,3 Anderson, D.L. and M.D. Howell. 1993. Implementation of the Everglades Surface Water Improvement and Management Plan in the EAA. Sugar J. 56(6):5-10.

1,3,6 Anderson, D.L. and Hutcheon Engineers. 1992. Reduction of the phosphorus loading in the EAA through control of sediments and suspended solids in drainage water (sediment control). FSCL. Presented to the SFWMD, SAGE Committee August. 44 pp.

2,4 Anderson, D.L., I.M. Ostrokolski, and A. Faber. 1989. Biochemical behavior and transport of phosphorus in the Lake Okeechobee basin, evaluations of the effects of soil amendments on P mobility using soil column leaching studies. Final Report, Task 1.4.2. West Palm Beach, Fl.: SFWMD. 129 pp.

6 Anderson, D.L. and D.L. Sites. 1994. Agricultural Best Management Practices and Surface Water Improvement and Management (S.W.I.M.). International Conference on Integrated Water

Resources Management. Inter. Ass. Water Quality. AquaTech, Amsterdam, The Netherlands, 26-29 September. Conference proceedings to be published in 1995, J. Water Sci. & Techn.

6 Andreis, J.H. 1992. Best Management Practices for on-farm phosphorus reductions through sediment control. Clewiston, Fl.: U.S. Sugar Corporation.

5 Ball, D.F. 1964. Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. Soil Sci. 15:84-92.

2,4 Bierman, James. 1993. A preliminary modeling analysis of phosphorus and phytoplankton dynamics in Lake Okeechobee, Florida: diagnostics and sensitivity analyses. West Palm Beach, Fl.: SFWMD. Manuscript.

7 Blom, G., E.H.S. van Duin, R.H. Aalderink, L. Lijklema and Cristian Toet. 1992. Modelling sediment transport in shallow lakes - interactions between sediment transport and sediment composition. Hydrobiologia 235/236:153-166.

6 Brown and Caldwell Consultants. 1992. Everglades Protection Project: Phase I, evaluation of alternative treatment technologies. Draft report Contract C-3051, Amendment 2. Submitted to SFWMD.

6 Brown and Caldwell Consultants. 1993. Everglades Protection Project: Phase II, evaluation of alternative treatment technologies. Preliminary draft report. Submitted to SFWMD.

6 Brown and Caldwell Consultants. 1993. Everglades Protection Project: evaluation of on-farm Best Management Practices. Submitted to SFWMD.

1, Brown and Caldwell Consultants. 1993. Technical Memorandum No.2: Daily flow and P-load data development. In: Contract C-3051, Amendment 6, draft report. Orlando, Fl.: Brown and Caldwell Consultants.

1 Burns & McDonnell. 1992. Everglades Protection Project: Technical Memorandum, historical discharge data for the Everglades Agricultural Area. Draft report. Submitted to SFWMD.

1,3 Burns & McDonnel. 1992. Everglades Protection Project: historical phosphorus loads for the Everglades Agricultural Area. Draft report. Submitted to SFWMD.

5 Campbell, R.B. 1939. Outline of the geologic history of peninsular Florida. Fla. Acad. Sci. Proc. 4:87-105.

1,2,3,4,6 CANVIRO Consultants Ltd. 1986. Preliminary phosphorus control considerations for EAA discharges to Lake Okeechobee. Prepared for FSCL.

2,4 Carey, J.S. and W.C. Huber. 1991. Lake Okeechobee Phosphorus Dynamics Study. Volume VIII: Assembly and time series analysis of historical flow and phosphorus data. Submitted to SFWMD. Contract No. C91-2393. Gainesville, Fl.: University of Florida, Department of Environmental Engineering. 225 pp.

1,3 CH2M HILL. 1978. Water quality studies in the Everglades Agricultural Area of Florida. Submitted to FSCL. Gainesville, Fl.: CH2M HILL, Inc.

1,3 CH2M HILL. 1979. Phase 3 water quality studies in the Everglades Agricultural Area of Florida. Submitted to FSCL. Gainesville, Fl.: CH2M HILL, Inc.

1,2,3,4,6 CH2M HILL. 1987. Analysis of control strategies for reduction of phosphorus loads to Lake Okeechobee from Special 298 Drainage Districts. Prepared for South Florida Conservancy District, South Shore Drainage District, East Shore Water Control District, East Beach Water Control District.

5,1,3 Clayton, B.S. 1943. Nature and extent of surface subsidence of the organic soils of the Everglades. Part I. Soil Sci. Soc. of Fla. Proc. V-A.

5 Clayton, B.S., J.R. Neller and R.V. Allison. 1942. Water control in the peat and muck soils of the Florida Everglades. Gainesville, Fl.: University of Florida, Agricultural Experiment Station. Bull. No. 378. 74 pp.

5 Cooke, C.W. 1929. Geology of Florida. Fla. Geol. Surv. 20th Ann. Rep.

1,3 Cooper, R.M. and J. Lane. 1988. An atlas of the Everglades Agricultural Area Surface Water Management Basins. West Palm Beach, Fl.: SFWMD.

2,4 Davis, F. and M. Marshall. 1975. Chemical and biological investigations of Lake Okeechobee, January 1973 - June 1974. Interim report. West Palm Beach, Fl.: SFWMD. Tech. Pub. 75-01.

5 Davis, J.H. Jr. 1946. The peat deposits of Florida. Fla. Bur. Geol. Bull. No. 30. Tallahassee, Fl.

1,3,2,4 Davis, S. 1982. Patterns of radiophosphorus accumulation in the Everglades after its introduction into surface water. West Palm Beach, Fl.: SFWMD. Tech. Pub. 82-02.

5,1,2,3,4 Davis, S.M. and J.C. Ogden, editors. 1994. Everglades. The Ecosystem and Its Restoration. Delray Beach, Fl.: St. Lucie Press. 826 pp.

3,6 DeGrove, J.M. 1991. An analysis of the 20-year use of a deep Broward County lime rock pit as a natural advanced wastewater treatment and groundwater recycling facility. Fort Lauderdale, Fl.: Florida Atlantic University/Florida International University Joint Center for Environmental and Urban Problems. 50 pp.

5,3 Diaz, O.A., D.L. Anderson and E.A. Hanlon. 1993. Phosphorus mineralization from Histosols of the Everglades Agricultural Area. J. Soil Sci. 156:178-185.

2,4 Dickinson, R.E., W.C. Huber, and C.D. Pollman. 1992. Lake Okeechobee Phosphorus Dynamics Study. Volume X: Modeling of phosphorus dynamics in the water-column. Final Report 1988-1991. Contract No. C91-2393. West Palm Beach, Fl.: SFWMD.

1,2 Dickson, K. 1980. 1980 Annual Report - SFWMD Water Quality Monitoring Network. West Palm Beach, Fl.: SFWMD. Report 10/80.

1,2,3,4 Dickson, F.G., A.C. Frederico and J.R. Lutz. 1978. Water quality in the Everglades Agricultural Area and its impact on Lake Okeechobee. West Palm Beach, Fl.: SFWMD. Tech. Pub. 78-3.

4,2,3 Dierberg, F.E. 1991. Lake Okeechobee Phosphorus Dynamics Study. Volume VI: Littoral zone characterization associated biochemical processes. Submitted to SFWMD. Melbourne, Fl.: Florida Institute of Technology.

4,3,2 Dierberg, F.E. 1992. The littoral zone of Lake Okeechobee as a source of phosphorus after drawdown. Environ. Manage. 16(3):371-380.

7 Dijkhuis, A.H., N.K. Hoekstra, L. Lijklema and S.E.A.T. van der Zee. 1992. Origin of peak concentrations of phosphate during high discharges in a rural watershed. Hydrobiologia 235/236:257-260.

7 Does, J. van der, P. Verstraelen, P. Boers, J. van Roestel, R. Roijackers and G. Moser. 1992. Lake restoration with and without dredging of P-enriched upper sediment layers. Hydrobiologia 233:197-210.

5 Draughtrey, Z.W., J.W. Gilliam and E.J. Kamprath. 1973. Phosphorus supply characteristics of acid organic soils as measured by desorption and mineralization. Soil Sci. 115:438-446.

5,1,3 Duxbury, J.M. and J.H. Peverly. 1978. Nitrogen and phosphorus losses from organic soils. J. Environ. Qual. 7:566-570.

2,4 Eutrophication of Lake Okeechobee. 1976. Submitted to FSCL. Black, Crow and Eidsness, Inc.

2,4 Federico, A., K. Dickson, C. Kratzer and F. Davis. 1981. Lake Okeechobee water quality studies and eutrophication assessment. West Palm Beach, Fl.: SFWMD. Tech. Pub. 81-02. 270 pp.

2,4,1,3 Flaig, E.G. and G. Ritter. 1989. Water quality monitoring of agricultural discharge to Lake Okeechobee. Pap. Amer. Soc. Agric. Eng. 89-2525:9-41.

2,4 Fluck, R.C., C. Fonyo and L. Stanislawsky. 1990. Land-use based phosphorus balances for Lake Okeechobee subbasins. Pap. Amer. Soc. Agric. Eng. 90-3024:17 pp.

3,4,1,2 Gale, P.M., K.R. Reddy and D.A. Graetz. 1992. Mineralization of sediment organic matter under anoxic conditions. J. Environ. Quality 21(3):394-400.

1,2,3,4 Germain, G. and J. Shaw. 1988. Surface Water Quality Monitoring Network SFWMD. West Palm Beach, Fl.: SFWMD. Tech. Pub. 88-03.

5 Given, P.H. and C.H. Dickenson. 1973. Biochemistry and microbiology of peats. Soil Biochemistry, Vol. 3:123-211. E.A. Paul and A.D. McLaren, editors. New York: Marcel Dekker.

1,3 Gleason, P. 1974. Chemical quality of water in Conservation Area 2A and associated canals. West Palm Beach, Fl.: SFWMD. Tech. Pub. 74-01.

6 Griffin, D.M. 1992. Dairy Best Management Practices & Buyout Project: the Lake Okeechobee drainage basin. Tallahassee, Fl.: FDACS. 14 pp.

5 Hammar, H.E. 1929. The chemical composition of Florida Everglades peat soils, with special reference to their inorganic constituents. Soil Sci. 28(1):1-13.

4 Haunert, D. 1988. Sediment characteristics and toxic substances in St. Lucie Estuary, Florida. West Palm Beach, Fl.: SFWMD. Tech. Pub. 88-10.

2,4 Havens, K. 1993. Historical trends in nutrient limitation in a sub-tropical lake, Lake Okeechobee, Florida, USA. West Palm Beach, Fl.: SFWMD. Manuscript.

2,4,6 Havens, K. 1993. Phosphorus reduction goals and limiting nutrient status in Lake Okeechobee, Florida, USA. West Palm Beach, Fl.: SFWMD. Manuscript.

6 Hutcheon Engineers. 1992. Preliminary evaluation of the limestone borrows for treatment of agricultural surface water. Report for FSCL. 19 pp.

3,1 Hutcheon Engineers, and T. Sturm. 1992. Impact of canal sediments on the total phosphorus loadings from the Everglades Agricultural Area (sediments). Prepared for FSCL. West Palm Beach, Fl. (5226.00) 46 pp.

6,3,1 Izuno, F.T. 1991. BMPs for phosphorus loading reductions in the EAA: future directions. Belle Glade, Fl.: EREC. pp. 53-59.

5,3,1 Izuno, F.T. and A.B. Blottcher. 1991. The effects of on-farm agricultural practices in the organic soils of the EAA on phosphorus and nitrogen transport - screening BMPs for phosphorus loadings and concentration reductions. Final report to SFWMD.

1,3 Izuno, F.T., C.A. Sanchez, F.J. Coale, A.B. Blottcher and D.B. Jones. 1991. Phosphorus concentrations in drainage water in the Everglades Agricultural Area. J. Environ. Quality 20(3):608-619.

2,4 James, Bierman. 1993. A preliminary modeling analysis of phosphorus and phytoplankton dynamics in Lake Okeechobee, Florida: calibration results. West Palm Beach, Fl.: SFWMD. Manuscript.

4,2 Janus, L.L. 1987. Evidence for eutrophication of Lake Okeechobee: declaration of net phosphorus sedimentation. *In* Seventh International Symposium, North American Lake Management Society, November 3-7, 1987, Orlando, Fl.

2,4 Jones, B.L. 1982. Lake Okeechobee water quality, April 1980-March 1981. West Palm Beach, Fl.: SFWMD. Tech. Memo 3/82.

2,4 Jones, B. 1983. Lake Okeechobee water quality - April 1981-March 1982. West Palm Beach, Fl.: SFWMD. Tech. Memo 1/83.

5 Jones, L.A. 1948. Soils, geology, and water control in the Everglades region. Gainesville, Fl.: University of Florida. Agricultural Experiment Station. Bull. No. 442. 168 pp.

2,4 Jones, Soballe. 1990. Lake Okeechobee Water Quality Monitoring - Annual Report, Year Five. West Palm Beach, Fl.: SFWMD. Tech. Memo 6/90.

5 Kipp, H.A. and F.F. Schafer. 1910. Investigations of water content of muck soils in Florida, including those of the Everglades. Mimeo.

1,3,5,2,4 Koch, M.S. 1991. Soil and surface water nutrients in the Everglades Nutrient Removal Project. West Palm Beach, Fl.: SFWMD. 91-04.

5 Koch, M.S. and K.R. Reddy. 1992. Distribution of soil and plant nutrients along a trophic gradient in the Florida Everglades. Soil Soc. Amer. J. 56:1492-1499.

7 Liere, L. van and Gulati, R.D., editors. 1992. Restoration and Recovery of Shallow Eutrophic Lake Ecosystems in The Netherlands. Proceedings of a conference held in Amsterdam, The Netherlands, 18-19 April 1991. Dordrecht, The Netherlands: Kluwer Academic Press. 287 pp.

7 Lijklema, L. 1986. Phosphorus accumulation in sediments and internal loading. Hydrolog. Bull. 20(1/2):213-224.

5 Lucas, R.E. 1980. Mobility of phosphorus and potassium in Everglades Histosols. Proc. 6th Intl. Peat Congress:413-417.

5 Lucas, R.E. 1982. Organic Soils (Histosols) formation, distribution, physical and chemical properties and management for crop production. Farm Science, Research Report 435. 77 pp.

1,3 Lutz, J. 1977. Water quality and nutrient loadings of the major inflows from the Everglades Agricultural Area to the Conservation Areas, Southeast Florida. West Palm Beach, Fl.: SFWMD. Tech Pub 77-06.

1,3 Lutz, J. 1977. Water quality characteristics of several Southeast Florida canals (supplement combined with text). West Palm Beach, Fl.: SFWMD. Tech Pub 77-04.

2,4 Marshal, M. and J. Gervin. 1977. Landsat investigations of water quality in Lake Okeechobee. West Palm Beach, Fl.: SFWMD. Report 2/77.

4 Mehta, A.J. 1989. Lake Okeechobee Phosphorus Dynamics Study. Volume IX: Sediment characterization - resuspension and deposition rates. Final report. Submitted to SFWMD. Contract No. C91-2393. Gainesville, Fl.: University of Florida, Coastal and Oceanic Engineering Department.

3,4 Moore, P.A. Jr., K.R. Reddy and D.A. Graetz. 1992. Nutrient transformation in sediments as influenced by oxygen supply. J. Environ. Quality 21(3):387-393.

7 Ndem, N.O. 1992. Potential phosphorus recharge in a eutrophic lake: The Holland Ankeveen Lake Case Study. Delft, Netherlands: International Institute for Hydraulic and Environmental Engineering. M.Sc. Thesis E.E. 86. 83 pp.

5,3,1 Neller, J.R. 1943. Nature and extent of surface subsidence of the organic soils of the Everglades. Part II. Soil Sci. Soc. of Fla. Proc. V-A.

5,3,1 Neller, J.R. 1944. Oxidation loss of lowland peat in fields with different water tables. Soil Sci. 58:195-204.

6,1,2,3,4 Newman, S., J. Roy and J. Obeysekera. 1993. The Florida Everglades Nutrient Removal Project. West Palm Beach, Fl.: SFWMD. Manuscript.

3,4,1,2 Pfeuffer, R.J. 1985. Pesticide residue monitoring in sediment and surface water bodies within the SFWMD. West Palm Beach, Fl.: SFWMD. Tech. Pub. 85-02.

4,2 Pollman, C.D. 1991. Lake Okeechobee Phosphorus Dynamics Study. Volume XI: Development of a phosphorus diagenetic model for sediments. Final report. Submitted to SFWMD. Gainesville, Fl.: KBN Engineering and Applied Science, Inc. 39 pp.

1,3,2,4 Reddy, K.R. and D.A. Graetz. 1991. Phosphorus dynamics in the Everglades Nutrient Removal System. Final report for 1990-1991. Submitted to the SFWMD, Contract No. C90-1168. Gainesville, Fl.: University of Florida, Soil Science Department.

3,4,1,2 Richardson, C.J. 1985. Mechanisms controlling phosphorus retention capacity in freshwater wetlands. Science 228:1424-1427.

2,4 Sawka, G.J., P. Ritter, B. Gunsalus and T. Rompot. 1992. Synoptic survey of dairy farms in the Lake Okeechobee basin: post-BMP water quality sampling. Pages 393-400 *in*: 10 Years of Controlling Agricultural Nonpoint Source Pollution: The RWCP Experience. Proc. National RWCP Symp. Sept 13-17, 1992, Orlando, Florida. Washington, DC: EPA.

4,5 Shaw, J. 1980. Hydrogeological investigation along eastern portion of Lake Okeechobee. West Palm Beach, Fl.: SFWMD. Report 8/80.

5,3,1 Shih, S.F., J.W. Mishol, J.W. Jones and D.L. Myhre. 1977. Modeling the subsidence of the Everglades organic soils. Paper No. 77-2034. ASAE 1977 Ann. Mtg., St. Joseph, MI.

1,3,5 Skaggs, R.W., J.W. Gilliam, T.J. Sheets and J.S. Barnes. 1980. Effect of agricultural land development on drainage waters in the North Carolina Tidewater region. Raleigh, NC: North Carolina State University. 164 pp.

2 South Florida Water Management District. 1974. Report on progress of hydrologic, water quality and land use studies in the Kissimmee River watershed and Lake Okeechobee. West Palm Beach, Fl.: SFWMD. Report 4/74.

1,2,3,4 South Florida Water Management District. 1978. District overview of cooperative water quality studies in the Everglades Agricultural Area and Lake Okeechobee. SFWMD and FSCL.

6,2,4 South Florida Water Management District. 1981. Water quality management strategy for Lake Okeechobee - executive summary. West Palm Beach, Fl.: SFWMD.

1,3 South Florida Water Management District. 1983. Water Quality Management Plan for the S-2 and S-3 Drainage Basins in the Everglades Agricultural Area. West Palm Beach, Fl.: SFWMD.

6,2,4 South Florida Water Management District. 1983. Water quality management strategy for Lake Okeechobee - executive summary addend. 3/83. West Palm Beach, Fl.: SFWMD.

2,4 South Florida Water Management District. 1988. Lake Okeechobee Water Quality Monitoring Program Annual Report-Year 3. West Palm Beach, Fl.: SFWMD. Tech. Memo 2/88.

2,4 South Florida Water Management District. 1988. Lake Okeechobee Water Quality Monitoring Program Annual Report-Year Four. West Palm Beach, Fl.: SFWMD. Tech. Memo 8/88.

6 South Florida Water Management District. 1990. Everglades Nutrient Removal Management Plan. West Palm Beach, Fl.: SFWMD. 68 pp.

6 South Florida Water Management District. 1992. Surface Water Improvement and Management Plan for the Everglades. Planning Document. West Palm Beach, Fl.: SFWMD. 202 pp.

6 South Florida Water Management District. 1992. Surface Water Improvement and Management Plan for the Everglades. Supporting Information Document. West Palm Beach, Fl.: SFWMD. 472 pp.

6 South Florida Water Management District. 1992. Surface Water Improvement and Management Plan for the Everglades. Appendices. West Palm Beach, Fl.: SFWMD. 472 pp.

5,3,1 Stephens, J.C. and Johnson, L. 1951. Subsidence of peat soils in the upper Everglades region of Florida. Soil Sci. Soc. Fla. Proc. XI: 191-237.

5,3,1 Stephens, J.C. and Johnson, L. 1951. Subsidence of peat soils in the Everglades region of Florida. Submitted to USDA, SCS. 16 pp.

2,4 Storch, W. 1975. Lake Okeechobee-Kissimmee basin water quality information (combined with L.O. proposals for management actions). West Palm Beach, Fl.: SFWMD. Report 3/75.

4,3 Syers, J.K., R.F. Harris and D.E. Armstrong. 1973. Phosphate chemistry in lake sediments. J. Environ. Quality 2(1):1-14.

5,3,1 U.S. Department of Agriculture. Subsidence of peat soils in Florida. Bur. of Agri. Engr., USDA. Bull. 1070.

5 Waksman, S.A. and K.R. Stevens. 1929. Contribution to the chemical composition of peat. I. Chemical nature of organic complexes in peat and methods of analysis. Soil Sci. 28:315-340.

1,3 Waller, B.G. and J.E. Earle. 1975. Chemical and biological quality of water in parts of the Everglades, southeastern Florida. USGS Water Resources Investigations 56-75.

5 Zelazny, L.W. and W.H. Carlisle. 1974. Physical, chemical, elemental and oxygen-containing functional group analysis of selected Florida Histosols. Pages 63-78 (Chap. 6) *in* Histosols. Special Publ. No. 6, Soil Sci. Soc. Amer., Madison, WI.

APPENDIX C

Hydraulic and Best Management Practice Research Needs in the EAA

Forrest T. Izuno
Everglades Research and Education Center
University of Florida

Research objectives related to hydraulics and Best Management Practices (BMPs) in the EAA are interrelated. Research scopes overlap and are applicable to the field, farm, and basin levels. The primary goal of such research must be to protect the environment while maintaining agricultural production at the current levels of quantity and quality. An equally important consideration is to ensure adequate water supply to meet the growing urban demand for potable water in south Florida. Research in the past has been rushed, scientifically incomplete, sporadic, and not part of a comprehensive plan to fairly serve agricultural, environmental, and urban interests. While numerous studies have been conducted relative to water quality and quantity, there are still many questions which must be answered in the interest of achieving sustainable agriculture given the ever increasing direct competition with environmental and urban demands.

One of the first issues that must be resolved is whether it is appropriate to view farm discharge water and P as absolute contributions to the basin. The concepts of net P loading and net water user or supplier have been discussed, but never resolved. A large number of sugarcane farms in the EAA are net assimilators of P where more water enters the farms in irrigation or rainfall than leaves in drainage water. This assessment does not even account for the P mineralized during soil oxidation or P exported in the crops. It is a simple but powerful realization that many farms are simply not contributing P to the basin. In fact, those farms actually filter P from rain and irrigation sources. Farm characteristics that lead to farms being net loaders or net assimilators need to be identified and applied across the EAA to allow researchers to focus attention in areas where the most P loading reduction is necessary. Obviously, one must look at the P concentrations as well as the volumes of water pumped to fully understand the process. For example, large volumes of water may enter the farm in relatively low concentrations while smaller volumes leave during drainage pumping at substantially higher concentrations. This leads directly to the question of which is more harmful to the environment; constant discharges of water with lower P concentrations or sporadic slug discharges of high P concentrations.

Another major question that requires resolution is what forms of P are actually detrimental to the environment. The current assumption is that total-P discharges lead to detrimental downstream environmental effects. Yet, it is generally accepted that some of the P attached to particulate matter is not readily available for plant uptake and can only be extracted by acid digestions. If this particulate P is in fact immobile then it may have no effect on the environment. The proportions of particulate and soluble P in the total-P entering and leaving the farms need to be determined. This determination will aid in the development of BMPs to control the P which is most detrimental to the south Florida water system. It will also help to determine what types of BMPs would be most effective in reducing total-P discharges. Currently, only a small database of this type exists.

In line with the above, the origins of the sediments or particulate P need to be determined. Researchers need to determine whether particulate P in discharge water comes from scouring of the channel bottom during drainage, detritus, or from field surface erosion driven by surface runoff or wind. In addition, the comparative effects of draining a farm block over the field surface or through the soil profile and/or rock layer must be determined. The results will lead to a more productive and focused BMP implementation effort.

Canal and ditch cleaning has been discussed as a BMP for reducing P loads leaving farms and increasing farm water storage capacities. It is, however, known that cleaning ditches stirs up sediment and breaks down the structure of the channel banks. To gain the benefits of ditch and canal cleaning without incurring the adverse effects associated with the activity revolves around timing and frequency.

Water can be held back on farms to a certain degree, dependent on the crops grown and time of year. Data need to be generated that specifically indicate when fields can be kept wetter than current practice and for how long without adverse crop effects. To keep water on farms, some growers are resorting to a moving flood system where water is moved from block to block around the farm. Currently this is being done on a trial and error basis. Research needs to be done to determine the extent to which such activities can be done without adverse crop effects. Additionally, it has been advised that no water from flooded fields should leave a farm directly. Rather, the water should be moved around the farm internally allowing the crops and soils to assimilate and adsorb P. This activity will affect soil fertility and crop production in the short and long terms. To what extent is unknown.

Soil oxidation is a major source of P in the EAA. Biological oxidation must be reduced to limit the amount of P available for leaching. Yet, the mineralized P also adds to the fertility pool from which crops may draw during growth. This change in P mineralization will change the fertilizer requirements for the crops. Potentially, reduced P mineralization could lead to increased fertilization requirements thus negating all pollution related benefits of reducing P mineralization. Attached to soil oxidation under the category of soil subsidence is surface water runoff and wind erosion of the soils. The amount of soil that leaves a field in these ways on an annual basis needs to be determined. Much of the eroded soils may end up in the drainage stream, adding to the P load.

Soil depths throughout the EAA have decreased dramatically since the area was canalized. Currently, growers are attempting to drain the same parcels using the same pump and ditch management schemes that have been in place for years. Ditch spacings and pumping capacities generally remain the same. Physical systems may have to more efficiently manage water on the farmland. More efficient water management could lead to reduced P loading, reduced soil subsidence, and better crops. The costs, benefits, and designs of improved water management systems must be researched.

Finally, when all is done at the farm level, it may be discovered that the farms themselves can serve as effective P filters. This may obviate the need for Stormwater Treatment Areas (STAs) at the magnitude currently being proposed. It must be understood, however, that in spite of sizable P loading reductions achieved at the farm outlets, the basin level load reduction may not be evident to the same extent at the South Florida Water Management District pump stations unless the management of the area canals is also improved. In fact, growers may not be able to fully implement P reduction BMPs unless the management of the receiving canals is changed to accommodate new irrigation and drainage water volume and timing requirements. Growers and basin water managers must develop integrated and complementary water management schemes to achieve the full benefits of the P reduction BMPs.

APPENDIX D

Evaluation of Critical Issues Related to Nutrient Retention in the Everglades Watershed

K. R. Reddy
Soil and Water Science Department
Institute of Food and Agricultural Sciences
University of Florida
106 Newell Hall
Gainesville, FL 32611

The Everglades Agricultural Area (EAA) comprises of 607,692 acres with peat depths ranging from < 1 foot to 10 feet deep. Because of drained conditions of EAA, these soils are biologically oxidized at a rate of approximately 1 inch per year. Soils of this area are classified based on soil peat depth. Results of soil subsidence study (US-SCS 1988) suggest that approximately 81% of 607,692 acres of EAA typically have a soil depth of <51 inches. By the year 2000, it is estimated that about 87% of the EAA soils will have peat depths of <36 inches, while about 45% of the soils will have peat depths of < 12 inches. Further extrapolation of these results (assuming 1 inch subsidence per year) suggests that by the year 2050 approximately 96% of the EAA will have peat depths < 12 inches. It should be noted that soil subsidence rates can decrease as the soil depth decreases, as a result of increased mineral matter and bulk density. At this time, information is not available on the rate of biological oxidation as a function of peat depth and associated increase in mineral matter and bulk density. At this time, it is difficult to predict the effect of soil loss on farming practices in the EAA. Apparently, sugarcane is currently being cultivated even on soils with peat depth of about 12 inches. However, soil loss can have significant impact on water management and water quality.

Soil loss as result of biological oxidation or natural fire will result in enrichment of phosphorus in the soil profile. As the organic matter is oxidized, organic phosphorus (which represents up to 80% of the total P) is converted into inorganic P. Depending on soil conditions and physico-chemical properties of the soils, inorganic P can be potentially leached during draining and flooding cycles. Soils with deep peat depths will have greater capacity to store soil moisture in the soil profile during the rainy season than shallow organic soils. In order to maintain optimal field moisture conditions, shallow organic soils need to be drained more frequently than soils with deep peat depths, thus resulting in the release of more nutrients. For example, in Lake Apopka Basin we have measured high P losses during drainage of shallow organic soils (105 kg P/ha year) than deep organic soils (34-72 kg P/ha year). However, under certain soil conditions, phosphorus retention capacity of organic soils can be increased as result of soil subsidence, primarily due to increased mineral matter and bulk density. At this time we do not have any experimental evidence to show that phosphorus retention capacity can increase with soil subsidence.

Soil subsidence can be significantly reduced by maintaining high water-table conditions and by creating partial anaerobic conditions in the soil. If the farming practices continue at current level, soil subsidence can result in more severe drainage water quality problems in the EAA during the next 50 years. However, this prediction is based on the assumption that soil subsidence will increase the phosphorus release into drainage water and frequency of drainage will be higher on shallow organic soils than deep organic soils.

Several questions need to be addressed before evaluating whether Stormwater Treatment Areas (STAs) are needed if 60 years from now 96% of the land area in the EAA has peat depths of less than 12 inches.

1. Will the land area under production agriculture decrease with time as the peat depth decreases due to soil subsidence?

2. What effect soil subsidence and shallow peat depths will have on water management and drainage water quality?

3. What type of crops will be grown on shallow organic soils, if the soils are not suitable for sugarcane production?

4. Will the phosphorus retention capacity of the soils increase with soil subsidence?

5. Will the land areas (shallow peat depths) not suitable for production agriculture be restored as wetlands?

There are several unknowns with regard to future of the EAA especially in the management and farming practices. At least during the next 50-60 years STAs will be necessary to abate the pollution from the EAA drainage water and protect the Everglades Protection Areas.

Issues Related to Stormwater Treatment Areas

Freshwater wetlands, swamps and marshes, and flooded soil systems have been used as a possible means of reducing N and P levels of wastewaters. To maximize the N and P removal rate as well as the net storage capacity of the wetlands, it is important to understand the biogeochemical processes responsible for nutrient removal. Wetland soil chemistry is very complex because of the interactions between organic and inorganic forms of nutrients and associated chemical and biological components. The degree of soil reduction in wetlands will have a significant impact on labile and non-labile pools of C, N and P, and ultimately their retention/release by these soils. These mechanisms need to be quantified for STA sites. Although N and C processes are important, emphasis is usually placed on P because in many systems P effluent quality dictates the design criteria for constructing nutrient removal systems.

P removal in wetlands primarily occurs through physical, chemical, and biological processes functioning in the soil-water column. A significant portion of floodwater and porewater N and P can also be removed through uptake by macrophytes and algae. Rate of N and P removal by these processes is influenced by the physico-chemical conditions that exist in the overlying water and in the underlying soil. Some of these conditions are: (1) dissolved O_2 in the water; (2) pH; (3) temperature; (4) residence time of water; (5) water depth; (6) mixing in the water column; and (7) presence of aquatic macrophytes and algae. Although the soil processes are important in controlling efficiency of a constructed marsh, the reactions occurring at the root-soil interface also play a significant role in C, N and P dynamics of a wetland. For example, oxygen transport capacity of wetland plants can play a significant role in decomposition of organic matter and N losses as a result of nitrification-denitrification reactions. The oxidized rhizosphere can also have a significant effect on P solubility in the root zone.

The soils at proposed STA sites are classified as Histosols and have been used for crop production (sugar cane, vegetables) for the last four decades. Conversion of these areas into a marsh will alter the physico-chemical properties of the soils, thus having a significant impact on the nutrient assimilatory capacity of the created marsh. Thus, a basic understanding of biogeochemical processes regulating P behavior in organic soils is necessary to determine the functioning of these constructed marshes.

Several critical issues need to be addressed immediately for successful establishment of constructed marsh for nutrient retention. Some of these issues related to soil processes are:

- How much P can be retained by STA soils and how long?
- How long will the initial soil nutrient release sustain upon creation of a marsh?
- How stable and permanent are the P compounds stored in the system?
- Short-term soil processes vs. long-term soil processes...which one controls water quality?

The success of the STA marsh depends on the management of water flow, which will require a thorough understanding of the hydrodynamic processes in the system. Both surface flow and sub-surface flow play a major role in nutrient retention. Thus, an accurate water budget is needed for evaluating the effectiveness of the STA

marsh. It is likely that percolation rates in these soils can be high and if the water flowing through the profile is forced through the underlying limestone, effective P removal can be achieved.

Full-Scale STA Operation

The success of full-scale STA depends on the management of hydrology. Vegetation only provides short-term storage, thus the cycling of nutrients during decay of detrital material dictates long-term storage. Cycling of these nutrients between live and detrital components of the marsh needs further evaluation. In a full-scale STA operation, management of soils and vegetation may be an expensive task, thus operation should focus on hydrology management. The current design of full-scale STA does not provide a mechanism to regulate effluent quality, instead it relies primarily on natural ecosystem processes. This does not guarantee the low discharge P limit required to be met by STA. The full-scale STA should consider a final filter with limestone or limestone berm to reduce P concentration to the lowest levels possible. Critical research issues for full-scale STA's are:

1. Determine hydrologic flow path in the system for optimal HRT and nutrient retention.
2. Spatial and temporal nutrient exchanges between soil-water-plant components.
3. Movement of water through underlying limestone layer and impact on water quality.
4. Evaluation of final limestone filter for effective P removal.
5. Water and nutrient budgets.
6. Determine long-term effectiveness of the system under extreme hydrologic conditions (drought vs. high rainfall conditions).

Experimental Cells

The experimental cells currently available provide an excellent opportunity to evaluate various management scenarios, and for possible implementation of successful techniques in full-scale STA operation. These cells should be evaluated to study the interaction between hydrology, vegetation and soil components.

1. Evaluate hydraulic and nutrient loading on effluent quality.
2. Wet/dry cycles and impacts on nutrient release or retention.
3. Soil amendments to bind native and added P.
4. Role of vegetation on nutrient storage and release.
5. Identify key biogeochemical processes regulating water quality and measure rates for inclusion in model.
6. Develop a model to evaluate the system's performance and identify critical processes.
7. Develop water and nutrient budgets.

Process Level Research—Laboratory and In-situ Conditions

Since the success of the marsh is evaluated based on the effluent P concentration, it is critical to conduct research related to the biogeochemical processes of P in these soils. Because the large proportion of P is bound in organic form, P release is directly related to organic matter decomposition. The STA marsh receives significant levels of SO_4^{2-}, thus SO_4^{2-} respiration can play a significant role in the breakdown of organic matter. Similarly, fluctuations in hydrology can stimulate microbial breakdown of organic matter and release of P. To develop a

complete understanding of the role of these soils, we need the following additional information on nutrient dynamics in the system.

- Characterization of organic forms of nutrients and their relative biodegradability. Determine the bioavailability of P forms in the influent and effluent water.
- Influence of aerobic, facultative anaerobic and obligate anaerobic respiration on decomposition of soil organic matter and release of nutrients. Establish the role of NO_3^- and SO_4^{2-} loading on breakdown of soil organic matter and release of P.
- P retention capacity of organic soils, as influenced by soil pH and redox conditions. Stability of various phosphatic compounds under these conditions.
- Determine the mechanisms of P retention by organic soils, and develop ways to increase P retention.
- P exchange between soil and the overlying floodwater as influenced by nutrient loading to the marsh. Establish the role of benthic activity, macrophytes and periphyton communities on P exchange rates.
- Determine the spatial and temporal effects on nutrient exchange between soils and the overlying water column.
- Determine the role of floodwater ysico-chemical properties on P solubility.
- Determine e interaction between detrital accumulation and decomposition and soil processes.
- Soil – P leaching studies – determine potential P leaching during downward flow through soil.
- Determine P retention by limestone during downward flow of water.
- Determine the effect of flooding duration – water-table depth fluctuation on P release/retention.
- Effects of draw-down and drying to reduce 'floc' layer in cattail area.
- Develop an internal nutrient budget for the marsh.
- Develop a mechanistic soil process model to synthesize experimental data and integrate into management models to optimize the functioning of the marsh.

SUBREGION 5:

EVERGLADES WATER CONSERVATION AREAS

BACKGROUND

The WCAs, comprising 3,554 km^2 (1,350 mi^2), represent an area equivalent to approximately one-third of the original Everglades landscape. These areas consist of five interconnected diked impoundments encompassing that portion of the remaining natural Everglades system situated on the topographic gradient of the Everglades watershed downslope (south) of Lake Okeechobee and immediately upslope (north) of ENP. The area is wedged between the developed Atlantic Coastal Ridge (Lower East Coast) on the east and the EAA and BCNP on the north and west (Figure 1). These impoundments were constructed in phased steps over a number of years, culminating in the current configuration in the early 1960s. The principal function of the units is water control for economic development. The system provides a compartmentalized detention reservoir for excess water from the EAA and parts of the LEC as well as accommodating flood discharges from Lake Okeechobee. The levee system on the east prevents flood waters from inundating the principally urban LEC while providing water supply for the agricultural lands and ENP. The areas further enhance the supply to the LEC by serving to recharge the Biscayne Aquifer, the primary drinking water source for the urban area, while retarding saltwater intrusion. All these functions are to be accomplished in a manner benefiting the considerable wildlife resources dependent on the system.

The WCAs are formed by earthen dikes and peripheral canals connected to the major drainage canal conveyance system traversing the EAA and East Coast Ridge. The WCAs have a combined storage capacity of 1,882,000 acre-ft through which the various functions of water storage, water supply, and flood control are accomplished. The three units are aligned north to south and connected serially with discharges from the upslope unit representing input to the unit immediately downslope. All receive direct inputs from rainfall, with the lower two units (WCA 2 and WCA 3) receiving additional inputs from the Miami and North New River canals. The latter two units are further subdivided to conserve surface water from excessive entrainment into the Biscayne Aquifer.

The predrainage landscapes of the WCAs consisted of complex mosaics of vegetative habitats interspersed variously on the low-relief, low-gradient peat bed that had accumulated over the past 5000 years. These vegetative habitats were products of the interaction of the plant communities and the natural forces of hydrology (both flow and hydroperiod) and fire, the same forces responsible for the ontogeny of the peat. The resultant was an enormously immense and heterogeneous complex of aquatic and vegetative structures. Today, the complex mosaics of tree islands, sawgrass (*Cladium jamaicense*) strands, wet prairies, and aquatic sloughs represent the natural remnants of this once vast complex.

The WCAs are critically important to wildlife resources of the Everglades ecosystem. The areas are rich in fish and wildlife, particularly wading birds (including the endangered wood stork), the endangered snail kite, and the American alligator. Grass shrimp, crayfish, and select fish species are well adapted to the periodic wet/dry regimens that characterize the Everglades. WCA 1 is operated by the FWS as the Arthur R. Marshall Loxahatchee NWR.

MAJOR ISSUES

The WCAs are precariously juxtaposed between urban development on the east and agricultural development to the north and west, concomitant with their ever increasing demands for flood protection and consumptive needs for water supply. By virtue of their spatial placement in the center of the hydrologic gradient, the highly managed nature of their input and output regimens, and the documented consequence of receiving the nutrient-enriched drainage of the surrounding agricultural and urban areas (SFWMD 1992), these areas are severely impacted by current water management operations of the C&SF Project and are integral to the restoration effort. These WCAs contain the last remnants of the tall-sawgrass landscape, as well as the bulk of deep marshes, wet

prairies, and tree island hammocks outside ENP (Light and Dineen 1994). Additionally the WCAs provide habitat for a diverse array of flora and fauna, including endangered species, particularly snail kites and wood storks. Since a major portion of the Kissimmee/Okeechobee and Atlantic Coast Ridge drainage are diverted to sea for regulatory flood control, the historic hydrologic throughput, or volume through these units, is severely reduced. The areas have been virtually isolated from the Kissimmee/Okeechobee watershed and the resultant sheetflow with all its natural variation that was a critical element in formation and ecological structure and function of the Everglades landscape. The impoundments instead serve to replace the historic inclined hydrologic gradient, formerly subject to overflow, with a series of stepped basins connected through control structures, which localize and minimize the forces of the flow that historically shaped and maintained the landscape structure of the system. In addition, by virtue of their hydrologic regulation schedules, these systems are practically decoupled from rainfall, becoming over-inundated in response to flood protection and overly dewatered in response to consumptive water supply demands in dry years. In addition there have been major altered hydroperiod impacts resulting from impoundment of these systems. Channelization coupled with impoundment has increased depth and hydroperiods at the southern end of the systems, while it has over-dewatered and shortened hydroperiods in the northern end. One resultant of the above combined modifications is extensive invasion by the exotic melaleuca (*Melaleuca quinquenervia*) as well as numerous exotic fish. Another is the shortening of the requisite water-level conditions in time and space, vital to successful wading bird reproduction (Frederick and Collopy 1989). This is particularly critical since these units provide major rookery and foraging habitat for wading birds in normal and dry years.

Excessive nutrient loading (particularly phosphorus) resulting from agricultural drainage into the system has severely altered ecological structure and function of vast areas within the WCAs (approximately 6000 acres in WCA 1 and 25,000 acres in WCA 2). In its natural state the Everglades ecosystem was essentially an oligotrophic system, deriving most of its nutrient input through atmospheric deposition. Concomitant with drainage and development of the EAA, the WCAs have become retention/detention systems for storage and elimination of agricultural drainage. The chronic introduction of drainage waters with elevated concentrations of nutrients (10-20 times background concentrations) has resulted in massive conversions of sawgrass and wet prairie communities to stands of robust cattails (*Typha* spp.) and cattail/sawgrass mixes, along with replacement of the typical periphyton mat communities by species mixes more reflective of deteriorated water quality.

In response to the issue of nutrient enrichment impacts, several levels of investigations of nutrient thresholds have been initiated. These range from dosing studies conducted in greenhouse experiments, to flume dosing studies, to gradient analyses. The efforts are sponsored by the Department of Interior, SFWMD, and the sugar industry. The principal investigators are Fred Sklar (SFWMD), Ron Jones (FIU), and Curtis Richardson (Duke University).

PREVIOUS SCIENCE PLANS

In addition to the SFERTF and the C&SF Project of the COE there are three other major initiatives, mandated by the State of Florida, intended to address deterioration of the Everglades system and provide measures for restoration. These are the Everglades SWIM Plan (SFWMD 1992) under Sections 373.451-373.4595, F.S.; the Marjorie Stoneman Douglas Act; and provisions of the 1994 Everglades Forever Act. All provide for extensive restoration to improve water quality, water quantity, and hydroperiods in the Everglades. All establish extensive science programs to evaluate hydrological needs of the Everglades and develop technology and BMPs designed to improve water quality.

In response to these mandates, the SFWMD developed the comprehensive Everglades Research Plan (SFWMD 1994) that describes efforts necessary to fulfill legislative and judicial mandates for reduction of pollutant loads to the Everglades (principally phosphorus) over the next several years. The ERP goal is twofold: 1) reduction of nutrient loads to acceptable levels (short-term) and 2) system-wide regulation of nutrient sources to restore physical, chemical, and biological integrity of the Everglades system (long-term). These goals closely parallel many of the objectives for Subregion 5 stated below (excerpted from SSG 1993). Six major objectives and science programs address these goals:

1. Optimize operation of STAs for nutrient removal. STAs were designed, in conjunction with farm BMPs, to achieve an average 80% phosphorus load reduction from the EAA. Additional studies are needed to determine methods to further reduce loads without increasing STA size.

2. Determine biogeochemical and hydrologic parameters that cause large-scale ecological change. Greater understanding is needed about how Everglades flora and fauna respond to nutrient gradients and altered hydroperiod in order to provide information for models and enable managers to adjust water resource decisions to achieve the goal of no ecological imbalance.

3. Develop tools for multiobjective management of water resources. Modeling tools will be built to evaluate tradeoffs among water quantity, water quality, and ecological integrity for existing, proposed, and potential water management scenarios. Specific tasks are to define hydroperiod and minimum flow requirements, determine range of water quality variation in natural and impacted areas, and define vegetation responses to changes in water quantity and quality.

4. Assess status and trends of wildlife communities. The natural variability of wildlife resources needs to be quantified to provide a baseline to evaluate ecological impacts of water management decisions.

5. Evaluate and optimize the effectiveness of BMPs. The relationships among rainfall, farm practices, and nutrient runoff need to be defined. Analysis of EAA runoff data and site characteristics should help improve BMP performance.

6. Determine non-nutrient water and sediment quality criteria that prevent ecological imbalance. Studies are needed to determine the extent to which non-nutrient water quality conditions (e.g., trace metals, pesticides, mercury) in the Everglades comply with existing standards and to determine new standards if necessary. A mass balance framework will be used to document changes over time as a results of management actions.

INFORMATION NEEDS

Major issues and information needs for Subregion 5 were identified through a process employing the Adaptive Environmental Assessment Approach. The process began with stating the intended objectives of the restoration project (both hydrological and ecological), followed by framing strategic questions that address information needs required to meet the objectives. This assessment was conducted in a 2-day workshop, in which invited participants with the necessary expertise addressed the multidisciplinary issues and scientific/technological approaches to resolving those issues. The sessions included scientists from Federal and State agencies, nongovernment organizations, universities, and the private sector. Scientists involved in development of the ERP were full participants in the process and were instrumental in helping to assure the approach outlined below was complementary to efforts outlined in the ERP.

It is important to note that, while the Subregion 5 information needs discussed below encompass several science initiatives similar to those in the ERP, the basic assumptions differ. The hydrologic and ecologic objectives driving the ERP assume continuance of the present configuration of water control structures with only slight modifications to accommodate hydrologic changes, principally in the form of modifications to current water regulation schedules (primarily manipulating hydroperiods), and operated within the context of current and projected demands for water supply and flood protection. The objectives set forth in the 1993 Science Subgroup report are targeted at hydrological and ecological restoration of the ecosystem, which could involve reconfiguration of the present water control structures, as well as changes in regulation schedules.

The objectives, science questions and information needs, and approaches culminating from the workshop are outlined below for both hydrological and ecological restoration of Subregion 5. Under each critical science question is information on the approach and tasks recommended to answer the question. This information is summarized by the flow chart in Figure 14.

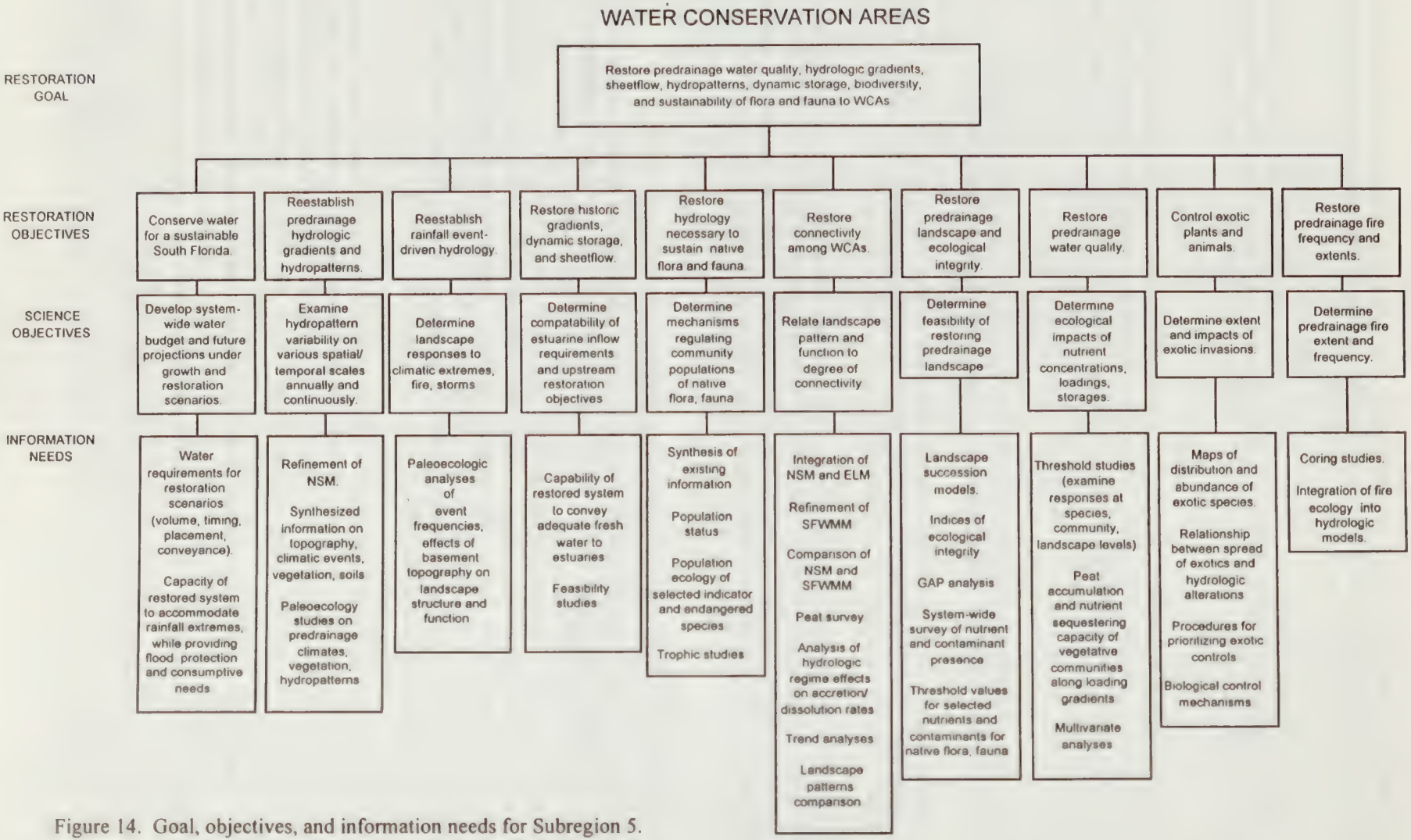

WATER CONSERVATION AREAS
RESTORATION GOAL
Restore predrainage water quality, hydrologic gradients, sheetflow, hydropatterns, dynamic storage, biodiversity, and sustainability of flora and fauna to WCAs
RESTORATION OBJECTIVES
Conserve water for a sustainable South Florida.
Reestablish predrainage hydrologic gradients and hydropatterns.
Reestablish rainfall event-driven hydrology.
Restore historic gradients, dynamic storage, and sheetflow.
Restore hydrology necessary to sustain native flora and fauna.
Restore connectivity among WCAs.
Restore predrainage landscape and ecological integrity.
Restore predrainage water quality.
Control exotic plants and animals.
Restore predrainage fire frequency and extents.
SCIENCE OBJECTIVES
Develop system-wide water budget and future projections under growth and restoration scenarios.
Examine hydropattern variability on various spatial/ temporal scales annually and continuously.
Determine landscape responses to climatic extremes, fire, storms
Determine compatability of estuarine inflow requirements and upstream restoration objectives
Determine mechanisms regulating community populations of native flora, fauna
Relate landscape pattern and function to degree of connectivity
Determine feasibility of restoring predrainage landscape
Determine ecological impacts of nutrient concentrations, loadings, storages.
Determine extent and impacts of exotic invasions.
Determine predrainage fire extent and frequency.
INFORMATION NEEDS
Water requirements for restoration scenarios (volume, timing, placement, conveyance).
Capacity of restored system to accommodate rainfall extremes, while providing flood protection and consumptive needs
Refinement of NSM.
Synthesized information on topography, climatic events, vegetation, soils
Paleoecology studies on predrainage climates, vegetation, hydropatterns
Paleoecologic analyses of event frequencies, effects of basement topography on landscape structure and function
Capability of restored system to convey adequate fresh water to estuaries
Feasibility studies
Synthesis of existing information
Population status
Population ecology of selected indicator and endangered species
Trophic studies
Integration of NSM and ELM
Refinement of SFWMM
Comparison of NSM and SFWMM
Peat survey
Analysis of hydrologic regime effects on accretion/ dissolution rates
Trend analyses
Landscape patterns comparison
Landscape succession models.
Indices of ecological integrity
GAP analysis
System-wide survey of nutrient and contaminant presence
Threshold values for selected nutrients and contaminants for native flora, fauna
Threshold studies (examine responses at species, community, landscape levels)
Peat accumulation and nutrient sequestering capacity of vegetative communities along loading gradients
Multivariate analyses
Maps of distribution and abundance of exotic species.
Relationship between spread of exotics and hydrologic alterations
Procedures for prioritizing exotic controls
Biological control mechanisms
Coring studies.
Integration of fire ecology into hydrologic models.

Figure 14. Goal, objectives, and information needs for Subregion 5.

Hydrological Restoration

Objectives

- Restore predrainage hydrologic gradients, hydropatterns, sheetflow and timing, as defined by output from the Natural System Model.

- Decompartmentalize the WCAs.

- Reestablish the modern historic natural rainfall-driven pattern of water discharge and timing between WCA 3A and BCNP, as defined by output from the NSM.

- Reestablish sheetflow from the EAA into the WCAs.

- Reestablish the modern historic hydrologic link between WCA 3A and WCA 3B as defined by output from the NSM.

- Provide delivery water to ENP that is in compliance with the Park's Outstanding Florida Water designation, Class III water quality standards, and terms of the 1991 Settlement Agreement and 1992 Court Order.

- Deliver water from the EAA into the WCAs that complies with Class III water quality standards and is of sufficient quality for preventing an imbalance of native flora and fauna and maintaining ecological integrity.

- Ensure water delivered to Loxahatchee NWR and other WCAs is in compliance with the Refuge's Outstanding Florida Water designation and terms of the 1991 Settlement Agreement and 1992 Court Order.

Critical questions and approaches

1. What were the predrainage sheetflow and hydropatterns (flow rate, volume, timing, water budget, spatial extent) over the range of rainfall/evapotranspiration conditions that occurred within annual to century time scales?

- Develop a series of spatially explicit grid-based hydrologic models (natural systems type) at various spatial/temporal scales to hindcast predrainage hydropatterns at scales that match critical system features (topographic gradients, waterway networks, flowways, etc.) and processes (rainfall extremes, overflow events, stage fluctuations, etc.) The models should be modified hierarchical versions of the current NSM of the SFWMD South Florida Water Management Model. A specific protocol should be developed to evaluate appropriateness of scales, both temporal and spatial to address the above question.

- Synthesize existing information on basement topography, historic topographic elevations, rainfall/climatic cycles, vegetation, lake stage and overflow, soil types, and basement geology. The geographic scope of the synthesis should encompass the entirety of the historic Everglades. This effort should be geospatially based for ease of facilitation into a GIS framework. Spatial databases generated in this task should provide the landscape framework for the spatially explicit hydrological models. Historic rainfall and climatic conditions should provide information for environmental correlates between hydrologic parameters and resulting landscape processes.

- Perform paleoecologic studies to fill information gaps for model input. (These studies should encompass the entirety of the historical Everglades.) Analyses should be designed to utilize marker horizons (both isotopic and stratigraphic) capable of depicting time-specific event sequences and system responses through time.

2. What hydrologic and associated forcing functions (fire, etc.) maintain the structure, function, and sustainability of the South Florida Ecosystem across spatial scales of km to 100s km?

Structure is considered spatial extent, heterogeneity of physiognomic features of the landscape, and associated large-scale/small-scale hydrologic gradients. Function is considered delivery of water downslope (throughput), flow (rate), dynamic storage, head, etc.

▸ Design a paleoecologic study based on stratigraphic analysis of cores strategically located throughout the Everglades. Through marker horizons (isotopic and geologic) develop a time series database for event sequences, frequencies, and extent (both spatial and temporal). Use dating techniques and botanical analyses to determine peat accumulation rates (site- and region-specific); historic dominant species composition and spatial extent of major vegetative landscapes (e.g., wet prairie, sawgrass, tree island complexes); fire frequency, extent, and magnitude; and landscape successional trends and discontinuities.

▸ Through analysis of peat/marl structure and charcoal remnants, determine extent and frequency of drought, fire, floods, hurricanes, etc. Determine the correlation between these variables and configuration and dynamics of historic vegetative communities within physiographic landscapes (as per Davis 1943). The objective is to determine the interacting effect of vegetation, topographic gradients, and historic rainfall patterns on hydrologic functioning of the system.

▸ Given the connection between basement topography and physiographic landscapes (Davis et al. 1994), determine relationship(s) between finer scale landscape features (tree islands, sloughs, etc.), hydrologic (and hydrologically controlled) forcing functions, and basement topography. This task will require integration of synthesized extant information, paleoecologic studies, and NSM studies.

3. What is the nature and degree of flow/hydropattern alterations due to compartmentalization? How do current regimes of flow and hydropatterns depart from historic regimes driven by rainfall and the natural hydrologic gradient that included sheetflow and system-wide dynamic storage? How has landscape distribution of productivity and biotic diversity been affected by the change from predominantly diffuse large-scale processes (dynamic storage/sheetflow and atmospheric deposition) to concentrated focused processes (canals, pumps, ditches, and point source of nutrients). More simply stated, how has the landscape been impacted by the barriers, canals, and water management of the C&SF Project?

▸ Analyze existing hydrologic conditions utilizing the SFWMM to characterize current patterns in hydroperiod, flow, storage, and gradients in the WCAs. Current spatial scale of the model may require modification to address the above questions.

▸ Utilize the NSM (see Question 1) to characterize historic patterns of flow and hydropatterns prior to compartmentalization. These models should be developed utilizing historic topography reconstructed from archived data or modeled from best available information sources. Historic vegetation/landscape features should be incorporated as spatially explicit Manning's coefficients.

▸ Both the SFWMM and the current version of NSM (Fennema et al. 1994) require considerable enhancement to address restoration questions at the scale required by this question. The following tasks would considerably augment the current capability:

- Conduct extensive and comprehensive topographic surveys in the WCAs.
- Determine specific Manning's coefficients for various vegetative types (particularly vegetative types that dominate landscape features).
- Determine percolation within the various reaches of the WCAs.
- Improve resolution of rainfall data and water delivery patterns.
- Validate model(s) with field measurements of water levels and flow.

▸ Compare output from current and historic models.

▸ Collect hydrologic data (flow, water level, etc.) to supplement existing data and model output to document the nature and extent of hydrologic alterations.

4. How are these alterations expressed in the existing landscape?

► Conduct an extensive survey of peat bed depths across the WCAs and ENP. Determine relationship between peat depths and current hydrologic conditions on affected areas. Utilizing cores with stratigraphic time markers generated in other tasks (see Question 2) determine correlations between peat accumulation rates and hydrologic regimes specific to the cored sites.

► Determine at various scales which patterns (elevation, vegetation, etc.) in the contemporary landscape are the result of changes in hydrologically controlled forcing functions as reflected in trend analysis and modeling.

- Conduct a high-resolution (< 1 km) topographic survey.
- Perform spatial trend analysis of pre- and post-compartmentalization topographic data. This will require synthesizing both historic and current information.
- Perform trend analysis (juxtaposition, location, abundance, orientation, succession) of pre- and post-compartmentalization vegetative features (sawgrass prairie, wet prairies, sloughs, and tree islands).
- Perform trend analysis of pre- and post-compartmentalization fire frequency, extent, intensity, and effects.
- Compare landscape patterns in WCA 1 and WCA 2 to investigate the role of sheetflow in structuring the vegetative landscape.

► Perform gradient analysis to determine relationships between hydrologic parameters and composition, abundance, and distribution of periphyton and macrophytes. This will require establishing permanent monitoring stations within a grid network traversing the various hydrologic gradients within the WCAs and periodically sampling vegetation plots for composition, percent cover, and biomass. A protocol based on a stratified approach could be employed to vary the temporal and spatial intensity of sampling.

► Utilizing the above information and the SFWMM, determine relationships between recent vegetative patterns and dynamics with hydrologic (and associated) forcing functions spatially across the WCAs.

► Integrate information obtained above with output of SFWMM and natural systems models into a spatially explicit landscape modeling capability, as per the SFWMD Everglades Landscape Model (ELM) (see "Modeling Ecologic Processes" chapter of this document), and compare the results for resolving impacts of compartmentalization. A landscape studies/modeling program should be developed that supports and integrates with hydrological modeling activities as well as the spatially explicit individually based ATLSS models being developed by ORNL and the NBS South Florida/Caribbean Field Laboratory. The program should dovetail with complementary modeling efforts underway within the SFWMD and build on existing capability, expanding the geographic and temporal scope of ELM and integrating a hierarchical capability to refine pixel element size for specific applications.

5. Is there adequate water available to support the desired system structure and functions? Is removal of the inter-unit dike and canal works of the WCAs feasible in terms of current or projected demands for water in the South Florida Ecosystem?

The tasks outlined below require considerable integration of the information synthesized from the previous science questions in addition to compiling a system-wide hydrologic budget.

► Develop system-wide (Kissimmee/Okeechobee/Everglades Watershed) water budget and projections of future water demands by consumptive users in the landscape (urban, agriculture, etc.).

► Develop a range of water requirements (volume, timing, placement, and conveyance requirements) to support critical natural system structure and functions. Inflow needs of the estuarine system are a critical element of this analysis.

▸ Determine the capacity of a restored system (consisting of ENP and the WCAs without any water control structures) to accommodate rainfall extremes and absorb stormwater runoff from adjacent developed areas.

6. Given the reduced spatial extent of the system, can adequate gradients and throughput be restored to support the freshwater inflow requirements of the downslope systems (i.e., ENP, Biscayne Bay, and other estuarine areas) without sacrificing critical system structure and functions?

Whole system integrity is one of the major tenets of the restoration initiative. There is genuine concern that any restorative fixes not be conducted on one part of the system at the cost of the ecological integrity of another. The loss of approximately 50% of the original wetlands raises concerns regarding conveyance capacity of the remaining wetland system to meet downstream inflow needs while maintaining desired ecologic structure and function.

▸ Based on critical water needs (amount, timing, etc.) of South Florida system components (estuary, urban, agriculture, northern Everglades, southern Everglades) investigate feasibility and impacts of various means for moving water from Lake Okeechobee to the estuaries and southern Everglades.

▸ Enhance landscape-level modeling capability (ELM, as per SFWMD) to interact with both SFWMM and "natural systems" hydrologic models. The enhanced model needs to be responsive to both hydroperiod/pattern and flow parameters in terms of predicting vegetative landscape responses. Investigate various scenarios of hydrologic restoration for their effect on landscape pattern and ability to maintain required hydroperiods and hydropatterns in a given area, while at the same time providing inflows required downslope.

7. What water quality is necessary to remove inorganic stressors on the system? What level of nutrients/contaminants trigger ecological impairment?

The Everglades SWIM Plan, Marjorie Stoneman Douglas Act, EFA, and Settlement Agreement between the U.S. Department of Justice and State of Florida concerning management of the Everglades all either require or identify the need to numerically interpret the narrative Class III nutrient water quality criteria and assess current and continuing response of the Everglades Ecosystem to nutrient loading. The following tasks are intended to provide information to resolve these issues.

▸ Conduct threshold studies for critical system components (periphyton, macrophytes, etc.). It is imperative to design appropriate experiments and bioassay techniques to be applied across the spectrum of ecological components, ranging from individual species to communities to even landscape features, to determine responses to the suite of both chronic and acute nutrient and other inorganic stressors impinging on the ecosystem. Approaches should include dosing studies in greenhouse and small field plots, metered chronic additions to flumed portions of major habitat types, and analysis of known gradients that may span major landscapes. Considerable effort will be required in experimental design to assure spatial and temporal scales are appropriate to the questions addressed.

▸ Perform gradient analysis of relationships between nutrients in water/soil and composition, abundance, and distribution of periphyton and macrophytes. These analyses require establishing combinations of grids and linear transects across the geologic, hydrologic, and water quality gradients comprising the South Florida Ecosystem landscape. Sampling intensity should be a function of gradient steepness and capture both abrupt and continuous gradients associated with peat depth, substrate type, hydroperiod, water depth, and water quality gradients, particularly those reflective of the influence of agricultural drainage. Each site should be characterized for community composition, relative cover, and biomass of macrophytic and periphyton communities. Samples of water and substrate should be taken for analysis of total phosphorus and nitrogen, conductivity, alkalinity, pH, hardness, and bulk density (substrate only).

▸ Determine peat accumulation and nutrient sequestering capacity of vegetative communities along gradients of nutrient inputs. Specific sites across the gradient grid network should be established for long-term monitoring/experimental manipulations in the form of dosing-type experiments to determine nutritive

assimilation capacity and specific threshold responses of the biotic community to nutrient loadings. Considerable innovation in technique experimentation should be encouraged to facilitate determinations of biotic responses.

8. What is the relative importance of hydrology and nutrients in modifying critical system components?

▸ Perform multivariate analyses on combined data sets of hydrology; nutrients; and composition, abundance and distribution of vegetation/periphyton generated in the gradient analysis described above.

Ecological Restoration

Objectives

- Restore predrainage populations of native flora and fauna, especially missing plant communities.
- Restore predrainage biodiversity.
- Reduce nutrient and contaminant import and export to levels adequate for maintaining ecological integrity.
- Control exotic plants and animals.
- Restore predrainage frequency and areal extent of fires to allow natural ecological processes to occur.

Critical questions and approaches

1. What forcing functions, operating on scales from patches to landscape, control distribution, abundance, and dynamics of periphyton, plant communities, aquatic invertebrates, fish, amphibians, reptiles, wading birds, snail kites, and mammals.

▸ Synthesize existing information, identify gaps, and design status and trend studies to determine distribution, abundance, and population dynamics of the above groups.

▸ Determine relationships (gradient analysis) between environmental factors (nutrients, contaminants, hydrology) and distribution, abundance, and population dynamics of the above groups (gradient studies, impacted vs. unimpacted areas).

▸ Determine trophic relationships in the system (stable isotope ratios, prey base studies, etc.).

▸ Develop a family of models to investigate relationships between controlling variables and flora and fauna components. Model types will include but are not limited to population dynamics, species-habitat relationships, niche delineation, landscape pattern recognition, and spatial trend analysis on distribution and abundance flora and fauna.

▸ Conduct studies to determine if fauna movements (fish, amphibians, reptiles) are altered due to compartmentalization.

2. How can predrainage vegetative landscape patterns be recreated within the context of existing spatial and hydrologic limitations?

▸ Develop a set (hierarchical) of landscape succession models to examine restoration scenarios, based on analysis of water requirements for system components (see hydrological objectives)

▸ Develop indices of "ecological integrity" at scales appropriate to individual target groups (periphyton→landscape).

- Conduct status and trend analyses of biodiversity as measured by vertebrate species richness.

- Combine information from natural system models with paleoecological data to determine correlations between hydrologic forcing functions and vegetative patterns and dynamics.

- Conduct time-series analyses on simulated hydroperiods and hydropatterns from hydrologic models and relate to patterns in vegetation data.

3. What constitutes impairment of ecological integrity?

- Develop a suite of indices to evaluate ecological integrity.

- Conduct studies to compare faunal differences along gradients and extremes of water/sediment quality.

4. What nutrients and contaminants are of concern?

- Using information on local, regional, and global sources and transport mechanisms, develop a list of nutrients and contaminants that warrant investigation.

5. What levels of nutrients and contaminants trigger impairment of ecological integrity?

- Using existing information on sources, transport, fate, and effect, determine measurement endpoints for nutrients and contaminants of concern.

- Conduct a system-wide survey of nutrient and contaminant presence and/or effect using the appropriate endpoints.

- Develop threshold values for selected nutrients and contaminants, using existing information, gradient analysis, or dosing studies.

6. What are the effects of exotics on system components and processes?

- Map distribution and abundance of exotic species.

- Determine linkages between the spread of exotics and alterations in critical ecosystem components and processes.

- Develop a procedure to prioritize exotics for control.

7. What are the best methods to control exotics?

- Investigate the use of biological controls for exotics.

- Determine which exotics may be controlled (or spread) by disturbances and changes in forcing functions as a result of compartmentalization or restoration.

8. What was predrainage fire frequency and areal extent of fire?

- Conduct coring studies to determine extent and frequency of fire.

9. Given the reduced spatial extent of the system, can patterns of fire frequency and extent be restored?

- Integrate fire ecology into hydrologic models.

10. Overriding question: What constitutes sustainability of the system?

BIBLIOGRAPHY

Bancroft, G.T., W. Hoffman, R.J. Sawicki, and J.C. Ogden. 1992. The importance of the Water Conservation Areas in the Everglades to the endangered wood stork (*Mycteria americana*). Conservation Biology 6(3):392-398.

Bancroft, G.T., A.M. Strong, R.J. Sawicki, W. Hoffman, and S.D. Jewell. 1994. Relationships among wading bird foraging patterns, colony locations, and hydrology in the Everglades. Pages 615-657 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Bartow, S.M. 1994. Historical changes in Everglades plant community structure and composition. Master's Project. Duke University, Durham, North Carolina.

Belanger, T.V., D.J. Scheidt, and J.R. Platko II. 1989. Effects of nutrient enrichment on the Florida Everglades. Lake and Reservoir Management 5(1):101-111.

Bennetts, R.E., M.W. Collopy, and J.J.A. Rodgers. 1994. The snail kite in the Florida Everglades: a food specialist in a changing environment. Pages 507-532 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Boyt, F.L., S.E. Bayley, and J.J. Zoltek. 1977. Removal of nutrients from treated municipal wastewater by wetland vegetation. Journal Water Pollution Control Federation 48:789-799.

Brim, M.S., D.H. Bateman, R.B. Jarvis, and G.A. Carmody. 1993. Mercury concentrations in largemouth bass and other fishes of the Arthur R. Marshall Loxahatchee National Wildlife Refuge and the Everglades National Park. Publication No. PCFO-EC9302. FWS, Panama City, Florida.

Browder, J.A. 1993. A capsulation of Everglades degradation activities and restoration efforts.

Browder, J.A., P.J. Gleason, and D.R. Swift. 1994. Periphyton in the Everglades: spatial variation, environmental correlates, and ecological implications. Pages 379-418 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Browder, J., C. Littlejohn, and D. Young. 1976. South Florida: seeking a balance of man and nature. UF, Gainesville, Florida.

Bryant, W.L., J.R. Richardson, and W.M. Kitchens. 1993. Vegetation relationships to sediment chemistry and hydrology in the Loxahatchee National Wildlife Refuge. Page 391 *in* M.C. Landin, editor. Wetlands. Proceedings of the 13th Annual Conference, New Orleans, Louisiana, June 1992. Society of Wetland Scientists, South Central Chapter, Utica, Mississippi.

Burns, L.A., and I.R.B. Taylor. 1979. Nutrient-uptake model in marsh ecosystems. Journal of the Technical Councils of ASCE 105(TC1):177-196.

Central and Southern Florida Flood Control District. 1950. A report on water resources of Everglades National Park Florida. Central and Southern Florida Flood Control District, West Palm Beach, Florida.

Chiang, C. 1994. The effects of nutrient additions on photosynthesis by cattail (*Typha domingensis* Pers.) and sawgrass (*Cladium jamaicense* Crantz) in the Everglades. Master's Project. Duke University Wetland Center, School of the Environment, Duke University, Durham, North Carolina.

Clark, J.R., M.A. Lewis, and A.S. Pait. 1993. Pesticide inputs and risks in coastal wetlands. Environmental Toxicology and Chemistry 12:2225-2233.

Clark, P. 1994. Restoring the Everglades. Miami Herald, January 13, [illegible]4.

Cohen, A.D., and W. Spackman. 1984. The petrology of peats from the Everglades and coastal swamps of southern Florida. Environments of South Florida: Past and Present II. Pages 352-374 *in* P.J. Gleason, editor. Miami Geological Society, Coral Gables, Florida.

Collopy, M.W., and J.P. Smith. 1991. Patterns of distribution and abundance and the reproductive and foraging ecology of wading birds. Pages 242-330 *in* J. V. Shireman, editor. Ecological Studies of the Litt[illegible]l and Pelagic Systems of Lake Okeechobee. Third Annual Report to the SFWMD, West Palm Beach, Florida.

Cooper, R.M., and J. Roy. 1991. An atlas of surface water management basins in the Everglades: The Water Conservation Areas and Everglades National Park. Water Resources Engineering Division, Department of Research and Evaluation, SFWMD, West Palm Beach, Florida.

Costanza, R., H.C. Fitz, J.A. Bartholomew, and E. DeBellevue. 1992. The Everglades Landscape Model (ELM): summary report of task 1, model feasibility assessment. Report to SFWMD by University of Maryland.

Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service, Washington, D.C.

Craft, C.B., J. Vymazal, and C.J. Richardson. 1995. Response of Everglades plant communities to nitrogen and phosphorus additions. Wetlands 15:258-271.

Craft, C.B. and C.J. Richardson. 1993. Peat accretion and N, P and organic C accumulation in nutrient enriched and unenriched Everglades peatlands. Ecological Applications 3(3):446-458.

Craft, C.B. and C.J. Richardson. 1993. Peat accretion and phosphorus accumulation along a eutrophication gradient in the northern Everglades. Biogeochemistry 22:133-156.

Craft, C.B., and C.J. Richardson. 1991. Determine if macrophyte composition changes in response to nutrient loadings (N, P, N + P) and water chemistry changes in response to nutrient loadings. Pages 180-216 *in* Effects of Nutrient Loadings and Hydroperiod Alterations on Control of Cattail Expansion, Community Structure and Nutrient Retention in the Water Conservation Areas of South Florida. Duke Wetland Center, Duke University, Durham, North Carolina.

Custer, T.W., and R.G. Osborn. 1977. Wading birds as biological indicators: 1975 colony survey. U.S. Fish and Wildlife Service, Washington, D.C.

Davis, J.H. Jr. 1943. The natural features of southern Florida, especially the vegetation and the Everglades. Geological Bulletin No. 25. Florida Geological Survey, Tallahassee, Florida.

Davis, S.M. 1982. Patterns of radiophosphorus accumulation in the Everglades after its introduction into surface water. SFWMD, West Palm Beach, Florida.

Davis, S.M. 1984. Cattail leaf production, mortality, and nutrient flux in Water Conservation Area 2A. Executive summary and discussion. SFWMD, West Palm Beach, Florida.

Davis, S.M. 1989. Sawgrass and cattail production in relation to nutrient supply in the Everglades. Pages 325-341 *in* R.R. Sharitz and J.W. Gibbons, editors. Freshwater Wetlands and Wildlife, CONF-8603101. DOE Symposium Series No. 61. U.S. Department of Energy, Office of Scientific and Technical Information, Oak Ridge, Tennessee.

Davis, S.M. 1990. Growth, decomposition and nutrient retention of sawgrass and cattail in the Everglades. SFWMD, West Palm Beach, Florida.

Davis, S.M. 1991. Growth, decomposition, and nutrient retention of *Cladium jamaicense* Crantz and *Typha domingensis* Pers. in the Florida Everglades. Aquatic Botany 40:203-224.

Davis, S.M., L.H. Gunderson, W.A. Park, J.R. Richardson, and J.E. Mattson. 1994. Landscape dimension, composition and function in a changing Everglades ecosystem. Pages 419-444 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Davis, S.M., and J.C. Ogden, editors. 1994. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Davis, S.M., and J.C. Ogden. 1994. Toward ecosystem restoration. Pages 769-796 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

DeAngelis, D.L. 1994. Synthesis: spatial and temporal characteristics of the environment. Pages 307-320 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Delany, M.F., J.U. Bell, and S.F. Sundlog. 1988. Concentrations of contaminants in muscle of the American alligator in Florida USA. Journal of Wildlife Diseases 24(1):62-66.

Delfino, J.J., T.L. Crisman, J.F. Gottens, B.E. Rood, and C.D.A. Earle. 1993. Spatial and temporal distribution of mercury in Everglades and Okefenokee wetland sediments. Final project report to SFWMD, USGS, and FDER. UF Department of Environmental Engineering Sciences, Gainesville, Florida.

Dewar, H. 1994. Prescription proposed for ailing Glades. January 13, 1994. The Miami Herald, Miami, Florida.

Dierberg, F.E. 1993. Decomposition of desiccated submersed aquatic vegetation and bioavailability of released phosphorus. Lake and Reservoir Management 8(1):31-36.

Dineen, J.W. 1985. Memorandum to P.B. Rhoads and F. Davis re: agricultural flow-way concept. SFWMD, West Palm Beach, Florida.

Dolan, T.J., S.E. Bayley, J.J. Zoltek, and A.J. Hermann. 1981. Phosphorus dynamics of a Florida freshwater marsh receiving treated wastewater. Journal of Applied Ecology 18:205- 219.

Eisemann, J., W.N. Beyer, R.E. Bennetts, and A. Morton. In review. Mercury residues in South Florida apple snails. Bulletin of Environmental Contamination and Toxicology.

Enos, P., and R.D. Perkins. 1977. Quaternary sedimentation in South Florida. Memoir 147. The Geological Society of America, Inc., Boulder, Colorado.

Exotic Pest Plant Council. 1993. Exotic Pest Plant Council's 1993 list of Florida's most invasive species. EPPC Committee on Invasive Species. Chairman: D. Austin, Department of Biological Sciences, FAU, Boca Raton, Florida.

Facemire, C.F. 1993. Contaminant concentrations in Florida raptor eggs. FWS, Vero Beach, Florida.

Fennema, R.J. 1992. Natural System Model, an evaluation of version 3.4. Report to NPS, ENP, Homestead, Florida.

Fennema, R.J., C.J. Neidrauer, R.A. Johnson, T.K. MacVicar, and W.A. Perkins. 1994. A computer model to simulate natural Everglades hydrology. Pages 249-289 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Fleming, D.M., D.L. DeAngelis, and W.F. Wolff. 1995. The importance of landscape in ecosystem integrity: the example of Everglades restoration efforts. Pages 202-217 *in* L. Westra and J. Lemons, editors. Perspectives on Ecological Integrity. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Fleming, D.M., W.F. Loftus, and M.B. Robblee. 1993. Critique of the wetland value assessment methodology and community models (WVA) document and an alternative approach. Report to C&SF Project Comprehensive Review Study, COE, Jacksonville, Florida. SFRC, ENP, Homestead, Florida.

Fleming, D.M., J. Schortemeyer, and J. Ault. In Press. Distribution and abundance of white-tailed deer in the Florida Everglades. Proceedings of the Florida Panther Conference, 1-3 November 1994, Fort Myers, Florida.

Fleming, D.M., J. Schortemeyer, and W. Hoffman. In press. Colonial wading bird distribution and abundance in the pre- and post-drainage Everglades landscapes. Oecologia.

Fleming, D.M., J. Schortemeyer, and W. Hoffman. In press. Colonial wading bird nesting in the pre- and post-drainage Everglades landscapes. Oecologia.

Fleming, D.M., W.F. Wolff, and D.L. DeAngelis. 1994. Importance of landscape heterogeneity to wood storks in the Everglades. Environmental Management 18(5):743-757.

Fleming, W.J., J.A. Rodgers Jr., and C.J. Stafford. 1984. Contaminants in wood stork eggs and their effects on reproduction, Florida, 1982. Colonial Waterbirds 7:88-93.

Flora, M.C., D.R. Walker, D.J. Scheidt, R.G. Rice, and D.H. Landers. 1988. The response of the Everglades marsh to increased nitrogen and phosphorus levels. ENP, Homestead, Florida.

Florida Department of Health and Rehabilitative Services. 1993. Florida health advisory for mercury in freshwater fish. FDHRS, Tallahassee, Florida.

Florida Panther Technical Subcommittee. 1989. Status report on mercury contamination in Florida panthers. A report of the Florida Panther Technical Subcommittee to the Florida Panther Interagency Committee. FGFWFC, Gainesville, Florida.

Frederick, P.C., R. Bjork, G.T. Bancroft, and G.V.N. Powell. 1992. Reproductive success of three species of herons relative to habitat in southern Florida. Colonial Waterbirds 15:192-201.

Frederick, P.C., and M.W. Collopy. 1988. Reproductive ecology of wading birds in relation to water conditions in the Florida Everglades. Florida Cooperative Fish and Wildlife Research Unit, School of Forest Resources and Conservation, UF, Gainesville, Florida.

Frederick, P.C., and M.W. Collopy. 1989. Nesting success of five Ciconiiform species in relation to water conditions in the Florida Everglades. Auk 106:625-634.

Frederick, P.C., and M.W. Collopy. 1989. Researcher disturbance in colonies of wading birds: effects of frequency of visit and egg-marking on reproductive parameters. Colonial Waterbirds 12:152-157.

Frederick, P.C., and M.W. Collopy. 1989. The role of predation in determining reproductive success of colonially nesting wading birds in the Florida Everglades. Condor 91:860-867.

Frederick, P.C., and G.V.N. Powell. 1994. Nutrient transport by wading birds in the Everglades. Pages 571-584 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Frederick, P.C., and M.G. Spalding. 1994. Factors affecting reproductive success of wading birds (Ciconiiformes) in the Everglades ecosystem. Pages 659-691 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Furutani, A., and J.W.M. Rudd. 1980. Measurement of mercury methylation in lake water and sediment samples. Applied and Environmental Microbiology 40(4):770-776.

Gleason, P.J., editor. 1984. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Gleason, P.J., and J.W. Spackman. 1974. Calcareous periphyton and water chemistry in the Everglades. Pages 146-181 *in* P.J. Gleason, editor. Environments of South Florida Present and Past II. Miami Geological Society, Coral Gables, Florida.

Gleason, P.J., P.A. Stone, D. Hallett, and M. Rosen. 1975. Preliminary report on the effect of agricultural runoff on the periphytic algae of Conservation Area 1. SFWMD, West Palm Beach, Florida.

Gleason, P.J., P.A. Stone, P. Rhoads, S.M. Davis, M. Zaffke, and L. Harris. 1975. The impact of agricultural runoff on the Everglades marsh located in the conservation areas of the Central and Southern Florida Flood Control District. C&SF FCD, West Palm Beach, Florida.

Grimshaw, H.J., M. Rosen, D.R. Swift, K. Rodberg, and J.M. Noel. 1993. Marsh phosphorus concentrations, phosphorus content and species composition of Everglades periphyton communities. Archiv für Hydrobiologie 128(3):257-276.

Gunderson, L.H., and C.S. Holling. 1991. Central and Southern Florida Ecosystem Modeling Reconnaissance Study. Results of July 1991 Workshop. UF, Gainesville, Florida.

Gunderson, L.H., and W.F. Loftus. 1993. The Everglades. Pages 199-255 *in* W.H. Martin, S.G. Boyce, and A.C. Echternacht, editors. Biodiversity of the Southeastern United States: Lowland Terrestrial Communities. John Wiley & Sons, New York.

Hand, J., and M. Friedemann. 1990. Mercury, largemouth bass, and water quality: a preliminary report. FDER, Bureau of Surface Water Management, Tallahassee, Florida.

Havens, K.E., and A.D. Steinman. 1995. Aquatic systems. Pages 121-151 *in* J.E. Rechcigl, editor. Soil Amendments: Impacts on Biotic Systems. Lewis Publishers, Boca Raton, Florida.

Hendry, C.D., P.L. Brezonik, and E.S. Edgerton. 1981. Atmospheric deposition of nitrogen and phosphorus in Florida. Pages 199-215 *in* S.J. Eisenreich, editor. Atmospheric Pollutants in Natural Waters. Ann Arbor Science, Ann Arbor, Michigan.

Hoffman, W., G.T. Bancroft, and R.J. Sawicki. 1990. Wading bird populations and distributions in the Water Conservation Areas of the Everglades: 1985 through 1988. NAS report to SFWMD, West Palm Beach, Florida.

Hoffman, W., G.T. Bancroft, and R.J. Sawicki. 1994. Foraging habitat of wading birds in the Water Conservation Areas of the Everglades. Page 585-614 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Holling, C.S., L.H. Gunderson, and C.J. Walters. 1994. The structure and dynamics of the Everglades system: guidelines for ecosystem restoration. Pages 741-756 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Hord, L.J., M. Jennings, and A. Brunell. 1990. Mercury contamination of Florida alligators. Pages 229-240 *in* Crocodiles: Proceedings of the 10th Working Meeting of the Crocodile Specialist Group of the Species Survival Commission of IUCN - the World Conservation Union, Gainesville, Florida, 23 April 1990. IUCN, Gland, Switzerland.

Ives, C. 1856. Military map of the peninsula of Florida, south of Tampa Bay.

Ives, J.C. 1856. Memoir to accompany a military map of the peninsula of Florida south of Tampa Bay. April 1856. War Department. Wynkoop Book and Job Printer, New York.

Jelks, H.L., J.R. Richardson, and W.M. Kitchens. 1993. Changes in the foraging patterns of wading birds (Ciconiiforms) in response to fluctuating hydrologic conditions in the impounded northern Everglades. Page 490 *in* M.C. Landin, editor. Wetlands. Proceedings of the 13th Annual Conference, New Orleans, Louisiana, June 1992. Society of Wetland Scientists, South Central Chapter, Utica, Mississippi.

Johnson, L. 1958. A survey of the water resources of Everglades National Park, Florida. Lamar Johnson, Consulting Engineer, Lake Worth, Florida.

Johnson, L. 1974. Beyond the Fourth Generation. UF, Gainesville, Florida.

Johnson, R.A., and J.C. Ogden. 1992. An assessment of hydrological improvements and wildlife benefits from proposed alternatives for the U.S. Army Corps of Engineers' General Design Memorandum for Modified Water Deliveries to Everglades National Park. Appendix J *in* Central and Southern Florida project for flood control and other purposes. Part 1, Agricultural and Conservation Areas. Supplement 54. General design memorandum and environmental impact statement. Modified water deliveries to Everglades National Park, Florida. COE, Jacksonville, Florida.

Jones, L.A. 1948. Soils, geology, and water control in the Everglades region. UF Agricultural Experiment Station, Gainesville, Florida.

Jordan, F. 1993. Species and assemblage level responses of fishes to the northern Everglades wetland landscape. Page 588 *in* M.C. Landin, editor. Wetlands. Proceedings of the 13th Annual Conference, New Orleans, Louisiana, June 1992. Society of Wetland Scientists, South Central Chapter, Utica, Mississippi.

Kadlec, R.H., and J.H. Alvord. 1989. Mechanisms of water quality improvement in wetland treatment systems. Pages 489-498 *in* D. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Kahl, M.P. Jr. 1964. Food ecology of the wood stork (*Mycteria americana*) in Florida. Ecological Monographs 34:97-117.

KBN Engineering and Applied Sciences. 1992. Mercury emissions in the atmosphere in Florida. Final report to FDER, Tallahassee, Florida.

Krantz, W.C., B.M. Mulhern, G.E. Bagley, A. Sprunt IV, F.J. Ligas, and W.B. Robertson Jr. 1970. Organochlorine and heavy metal residues in bald eagle eggs. Pesticides Monitoring Journal 4(3):136-140.

Kushlan, J.A., and P.C. Frohring. 1986. The history of the southern Florida wood stork population. Wilson Bulletin 98(3):368-386.

Lambou, V.W., T. Barkay, R.S. Braman, J.J. Delfino, J.J. Jansen, D. Nimmop, J.W. Parks, D.B. Parcella, J. Rudd, D. Schultz, J. Stober, C. Watras, J.G. Wiener, G. Gill, J. Huckabee, and B. Rood. 1991. Mercury Technical Committee interim report. Environmental Monitoring & Wet Environments Research Program, Center For Biomedical & Toxicological Research and Waste Management, FSU, Tallahassee, Florida.

Lange, T.R., F.J. Ware, and H.E. Royals. In preparation. Range and extent of mercury contamination in fish from the Florida Everglades. FGFWFC, Eustis, Florida.

Larsen and Associates. 1992. South Florida Limestone Mining Coalition Year 2050 Fresh Water Lake Belt Plan. Larsen and Associates, Miami, Florida.

Light, S.S., and J.W. Dineen. 1994. Water control in the Everglades: a historical perspective. Pages 47-84 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Loftus, W.F., J.D. Chapman, and R. Conrow. 1990. Hydroperiod effects on Everglades marsh food webs, with relation to marsh restoration efforts. Pages 1-22 *in* G. Larson and M. Soukup, editors. Fisheries and Coastal Wetlands Research, Volume 6. Proceedings of the 1986 Conference on Science in The National Parks, Fort Collins, Colorado, 13 July 1986. NPS and The George Wright Society, Fort Collins, Colorado.

Loftus, W.F., R.A. Johnson, and G.H. Anderson. 1992. Ecological impacts of the reduction of groundwater levels in short-hydroperiod marshes of the Everglades. Pages 199-208 *in* J.A. Stanford and J.J. Simons, editors. First International Conference on Ground Water Ecology, Tampa, Florida, 26 April 1992. EPA, AWRA, and Ecological Society of America.

Lowe, E.F. 1983. Distribution and structure of floodplain plant communities in the upper basin of the St. Johns River, Florida. SJRWMD, Palatka, Florida.

Lowe, E.F. 1986. The relationship between hydrology and vegetational pattern within the floodplain marsh of a subtropical, Florida lake. Florida Scientist 49(4):213-233.

Lutz, J.R. 1977. Water quality and nutrient loadings of the major inflows from the Everglades Agricultural Area to the Conservation Areas, Southeast Florida. SFWMD, West Palm Beach, Florida.

Mazzotti, F.J., and L.A. Brandt. 1994. Ecology of the American alligator in a seasonally fluctuating environment. Pages 485-505 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

McPherson, B.F. 1973. Vegetation in relation to water depth in Conservation Area 3, Florida. USGS, Tallahassee, Florida.

McPherson, B.F., B.G. Waller, and H.C. Mattraw. 1976. Nitrogen and phosphorus uptake in the Everglades Conservation Areas, Florida, with special reference to the effects of backpumping runoff. USGS, Tallahassee, Florida.

Meyer, F.W. 1971. Seepage beneath Hoover Dike Southern Shore of Lake Okeechobee, Florida. Report of Investigations No. 58. USGS, Tallahassee, Florida.

Millar, P.S. 1981. Interim progress report: water quality analysis in the Water Conservation Areas 1978 and 1979. SFWMD, West Palm Beach, Florida.

Miller, S.J., G.L. Warren, M.J. Vogel, J.G. Wullschleger, and L.J. Davis. 1990. Lake Okeechobee-Kissimmee River-Everglades resource evaluation project. FGFWFC, Okeechobee, Florida.

Milleson, J.F. 1980. Chlorinated hydrocarbon pesticide residues in freshwater fishes within the South Florida Water Management District. SFWMD, West Palm Beach, Florida.

Morse, N.J. 1994. Environmental contaminants in Everglade snail kite nestlings (*Rostrhamus sociabilis plumbeus*) from central Florida. FWS, Environmental Contaminants Program, Vero Beach, Florida.

Nash, L. 1993. Water quality and health. Pages 25-39 *in* P.H. Gleick, editor. Water in Crisis. Oxford University Press, New York.

National Audubon Society. 1994. Report on water supply preserves. Everglades Restoration Campaign, NAS, Miami, Florida.

National Biological Service. 1993. Scope of work for completion of an across trophic level system simulation (ATLSS) for the freshwater areas of the Everglades and Big Cypress Swamp. South Florida Field Office, NBS, Miami, Florida.

Nearhoff, F.L. 1992. Nutrient-induced impacts and water quality violations in the Florida Everglades. FDER, Tallahassee, Florida.

Newman, S., J. Roy, and J. Obeysekera. 1993. The Florida Everglades nutrient removal project. SFWMD, West Palm Beach, Florida.

Newman, S., J. Schutte, J.B. Grace, K. Rutchey, T. Fontaine, N. Campbell, K.R. Reddy, and M. Pietrucha. In review. Factors influencing cattail abundance in the northern Everglades. SFWMD, West Palm Beach, Florida.

Newsline. September 1993. Scientists deploying fungus in *Melaleuca* battlefield. Newsline, IFAS, UF.

Nichols, D.S. 1983. Capacity of natural wetlands to remove nutrients from wastewater. Journal Water Pollution Control Federation 55(5):495-505.

Ogden, J.C. 1978. Recent population trends of colonial wading birds on the Atlantic and Gulf coastal plains. Pages 135-153 *in* A. Sprunt IV, J.C. Ogden, and S. Winckler, editors. Wading birds. Research Report 7, NAS, New York.

Ogden, J.C., W.B. Robertson, G.E. Davis, and T.W. Schmidt. 1974 (revised). Pesticides, polychlorinated biphenyls and heavy metals in upper food chain levels, Everglades National Park and vicinity. South Florida Environmental Project: Report D1-SFEP-74-16. ENP, Homestead, Florida.

Pait, A.S., A.E. De Souza, and D.R.G. Farrow. 1992. Agricultural pesticide use in coastal areas: a national summary. NOAA, Rockville, Maryland.

Pait, A.S., A.E. De Souza, D.R.G. Farrow, and P.A. Pachecho. 1989. Agricultural pesticide use in estuarine drainage areas: a preliminary summary for selected pesticides. NOAA, Rockville, Maryland.

Parker, G. 1984. Hydrology of the pre-drainage system of the Everglades in southern Florida. Pages 28-37 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past. Miami Geological Society, Coral Gables, Florida.

Parker, G.G., G.E. Ferguson, S.K. Love, and others. 1955. Water resources of southeastern Florida with special reference to the geology and ground water of the Miami area. Geological Survey Water-Supply Paper 1255. GPO, Washington, D.C.

Penn & Schoen Associates. 1993. Focus groups on the Everglades with homeowners June 22-23, 1993. SFWMD, West Palm Beach, Florida.

Pfeuffer, R.J. 1985. Pesticide residue monitoring sediment and surface water bodies within the South Florida Water Management District. SFWMD, West Palm Beach, Florida.

Pfeuffer, R.J. 1991. Pesticide residue monitoring in sediment and surface water within the South Florida Water Management District, Volume 2. SFWMD, West Palm Beach, Florida.

Pope, K.R. 1991. The relationship of vegetation to sediment chemistry and water level variance on the Arthur R. Marshall Loxahatchee National Wildlife Refuge. UF, Gainesville, Florida.

Qualls, R.G., and C.J. Richardson. 1995. Forms of soil phosphorus along a nutrient enrichment gradient in the northern Everglades. Soil Science 160:183-198.

Qualls, R.G., and C.J. Richardson. In review. Geochemistry and microbial availability of dissolved organic nutrients in the Everglades of Florida. Ecology.

Rader, R.B. 1994. Macroinvertebrates of the northern Everglades: Species composition and trophic structure. Florida Scientist 57:22-23.

Rader, R.B., and C.J. Richardson. 1992. The effects of nutrient enrichment on algae and macroinvertebrates in the Everglades: a review. Wetlands 12:121-135.

Rader, R.B., and C.J. Richardson. 1994. Response of macroinvertebrates and small fish to nutrient enrichment in the Northern Everglades. Wetlands 14(2):134-146.

Raikes, J.A. 1992. Effects of salinity and hydroperiod on the relative growth of sawgrass and cattail. Master's Project. Duke University Wetland Center, School of the Environment, Duke University, Durham, North Carolina.

Rattner, B. 1993. Mercury and pesticides in the Everglades snail kite. Unpublished memo. FWS, Patuxent Wildlife Research Center, Patuxent, Maryland.

Reeder, P.A., and S.M. Davis. 1983. Decomposition, nutrient uptake and microbial colonization of sawgrass and cattail leaves in Water Conservation Area 2A. SFWMD, West Palm Beach, Florida.

Richardson, C.J., and C.B. Craft. 1990. Phase one: a preliminary assessment of nitrogen and phosphorus accumulation and surface water quality in Water Conservation Areas 2A and 3A of South Florida. Annual Report. Duke Wetland Center Publication 90-01. School of Forestry and Environmental Studies, Duke University, Durham, North Carolina.

Richardson, C.J., and C.B. Craft. 1993. Effective phosphorus retention in wetlands -- fact or fiction? Pages 271-282 *in* G.A. Moshiri, editor. Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Boca Raton, Florida.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, and R.B. Rader. 1991 (August). Annual Report. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 91-08. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, R.B. Rader, and R.R. Johnson. 1991 (September). Annual Report. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 91-09. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, R.B. Rader, L. Sutter, and J. Vymazal. 1992 (March). Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 92-08. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, R.B. Rader, L. Sutter, and J. Vymazal. 1992 (June). Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure

and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 92-09. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, R.B. Rader, L. Sutter, and J. Vymazal. 1992 (September). Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 92-10. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, R.B. Rader, L. Sutter, and J. Vymazal. 1992 (December). Annual Report. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 92-13. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, R.B. Rader, L. Sutter, and J. Vymazal. 1993 (March). Final Annual Report Appendices, Volume II. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 92-12. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, J. Stevenson, P. Vaithiyanathan, and J. Zahina. 1993 (March). Quarterly Report, January - March 31, 1993. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 93-01. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, R.B. Rader, L. Sutter, and J. Vymazal. 1993 (April). Annual Report (Revised). Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 92-11. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, J. Stevenson, P. Vaithiyanathan, and J. Zahina. 1993 (July). Quarterly Report, April 1 - July 31, 1993. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 93-02. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, P. Vaithiyanathan, and J. Zahina. 1993 (October). Quarterly Report, August 1 - October 31, 1993. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 93-03. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.G. Qualls, J. Stevenson, P. Vaithiyanathan, and J. Zahina. 1994 (January). Quarterly Report, November 1, 1993 - January 31, 1994. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 94-01. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, J. Stevenson, P. Vaithiyanathan, and J. Zahina. 1994 (April). Quarterly Report, February 1 - April 15, 1994. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 94-02. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.G. Qualls, J. Stevenson, and P. Vaithiyanathan. 1994 (July). Annual Report. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 94-08. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.G. Qualls, J. Stevenson, P. Vaithiyanathan, and J. Zahina. 1994 (October). Quarterly Report, July 16 - October 15, 1994. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 94-09. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B. Craft, R.R. Johnson, R.G. Qualls, J. Stevenson, P. Vaithiyanathan, and J. Zahina. 1995 (January). Quarterly Report, October 16, 1994 - January 15, 1995. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 95-01. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., C.B Craft, R.G. Qualls, J. Stevenson, P. Vaithiyanathan, and J. Zahina. 1995 (April). Quarterly Report, January 16, 1995 - April 15, 1995. Effects of nutrient loadings and hydroperiod alterations on control of cattail expansion, community structure and nutrient retention in the Water Conservation Areas of South Florida. Duke Wetland Center Publication 95-02. School of the Environment, Duke University, Durham, North Carolina.

Richardson, C.J., and P. Vaithiyanathan. 1995. Phosphorus sorption characteristics of Everglades soils along a eutrophication gradient. Soil Science Society of America Journal 59:1782-1788.

Richardson, J.R., W.L. Bryant, and W.M. Kitchens. 1993. Spatial relationships of vegetation, water quality, and hydrology in a northern Everglades ecosystem. Pages 401-405 *in* M.C. Landin, editor. Wetlands. Proceedings of the 13th Annual Conference, New Orleans, Louisiana, June 1992. Society of Wetland Scientists, South Central Chapter, Utica, Mississippi.

Richardson, J.R., W.L. Bryant, and W.M. Kitchens. 1993. A spatial hydrologic model of Loxahatchee National Wildlife Refuge and its integration into a GIS analysis. Pages 450-454 *in* M.C. Landin, editor. Wetlands, Proceedings of the 13th Annual Conference, New Orleans, Louisiana, June 1992. Society of Wetland Scientists, South Central Chapter, Utica, Mississippi.

Richardson, J.R., W.L. Kitchens, J.E. Mattson, and K.R. Pope. 1990. An evaluation of refuge habitats and relationships to water quality, quantity, and hydroperiod. UF, Gainesville, Florida.

Robertson, W. B. Jr., and P.C. Frederick. 1994. The faunal chapters: contexts, synthesis, and departures. Pages 709-737 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Robertson, W. B. Jr., and J.A. Kushlan. 1984. The southern Florida avifauna. Pages 219-257 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Roelke, M.E. 1990. Florida panther biomedical investigation. Bureau of Wildlife Research, FGFWFC, Gainesville, Florida.

Roelke, M.E., D.P. Schultz, C.F. Facemire, and G.E. Royals. 1991. Mercury contamination in Florida panthers. A report of the Florida Panther Technical Subcommittee to the Florida Panther Interagency Committee. FGFWFC, Gainesville, Florida.

Scheidt, D.J. 1989. Pesticides and Everglades National Park: South Florida use and threat. Pages 365-375 *in* D.W. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Scheidt, D.J., M.D. Flora, and D.R. Walker. 1989. Water quality management for Everglades National Park. Pages 377-390 *in* D.W. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Shih, G., W. Abtew, and J. Obeysekera. 1993. Sampling strategies and the accuracy of nutrient load calculation for agricultural runoff events. SFWMD, West Palm Beach, Florida.

Silveira, J.E., J.R. Richardson, and W.M. Kitchens. 1993. A geographic information systems model of fire damage and vegetation recovery in the Everglades. Pages 455-459 *in* M.C. Landin, editor. Wetlands. Proceedings of the 13th Annual Conference, New Orleans, Louisiana, June 1992. Society of Wetland Scientists, South Central Chapter, Utica, Mississippi.

Soil Conservation Service. 1947. Florida Everglades Region generalized land conditions. Map. USDA, SCS.

Soil Conservation Service. 1978. Soil Survey of Palm Beach County Area, Florida. USDA, SCS.

South Florida Water Management District. 1992. Surface water improvement and management plan for the Everglades . SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1993. Draft working document in support of the Lower East Coast Regional Water Supply Plan. SFWMD Planning Department, West Palm Beach, Florida.

South Florida Water Management District. 1994. Everglades Research Plan. SFWMD, West Palm Beach, Florida.

South Florida Water Management District Regional Modeling Group. 1994. Agenda of the Workshop on Uncertainties in Two Regional Hydrologic Simulation Models (SFWMD and NSM).

Spalding, M.G., J.P. Smith, and D.J. Forrester. In press. Experimental and natural infections of *Eustrongylides ignotus*: effect on growth and survival of nestling wading birds. Auk.

Stedinger, J.R., and D.P. Loucks. 1994. SFWMD Workshop on Reduction of Risk and Uncertainties in Regional Hydrologic Simulation Models: additional material on sensitivity analysis. SFWMD, West Palm Beach, Florida.

Steward, K.K., and W.H. Ornes. 1975. Assessing a marsh environment for wastewater renovation. Journal Water Pollution Control Federation 47(7):1880-1891.

Steward, K., and W.H. Ornes. 1975. The autecology of sawgrass in the Florida Everglades. Ecology 56:162-171.

Sundlof, S.F., D.J. Forrester, N.P. Thompson, and M.W. Collopy. 1986. Residues of chlorinated hydrocarbons in tissues of raptors in Florida. Journal of Wildlife Diseases 22(1):71-82.

Sutter, L.A. 1992. Effects of phosphorus concentrations and water depth on sawgrass (*Cladium jamaicense* Crantz) growth and nutrient uptake. Master's thesis. Duke University Wetland Center, School of the Environment, Duke University, Durham, North Carolina.

Sutter, L.A., J. Vymazal, C.B. Craft, and C.J. Richardson. 1993. Effects of phosphorus loading and hydroperiod on sawgrass, *Cladium jamaicense*. Page 467 *in* M.C. Landin, editor. Wetlands. Proceedings of the 13th Annual Conference, New Orleans, Louisiana, June 1992. Society of Wetland Scientists, South Central Chapter, Utica, Mississippi.

Swift, D.R. 1981. Preliminary investigations of periphyton and water quality relationships in Everglades Water Conservation Areas. SFWMD, West Palm Beach.

Swift, D.R. 1984. Periphyton and water quality relationships in the Everglades Water Conservation Areas. Pages 97-117 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Swift, D.R., and R.B. Nicholas. 1987. Periphyton and water quality relationships in the Everglades Water Conservation Areas: 1978-1982. SFWMD, West Palm Beach, Florida.

Symons, J.M., T.A. Bellar, J.K. Carswell, J. DeMarco, K.L. Kropp, G.G. Robeck, D.R. Seeger, C.J. Slocum, B.L. Smith, and A.A. Stevens. 1975. National organics reconnaissance survey for halogenated organics. Journal American Water Works Association 67(11):634-647.

Terczak, E.F. 1980. Aquatic macrofauna of the Water Conservation Areas. SFWMD, West Palm Beach, Florida.

U.S. Army Corps of Engineers. 1949. Comprehensive Report on Central and Southern Florida for Flood Control and Other Purposes. GPO, Washington, D.C.

U.S. Army Corps of Engineers. 1991. Simulation model of south central Florida hydrologic ecosystem. Reconnaissance report. COE, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1992. Central and Southern Florida Project for Flood Control and Other Purposes. Part 1, Agricultural and Conservation Areas. Supplement 54. General design memorandum and environmental impact statement. Modified water deliveries to Everglades National Park, Florida. COE, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1992. Central and Southern Florida Project for Flood Control and Other Purposes. Part 1, Agricultural and Conservation Areas. Supplement 54. General design memorandum. Appendices. Modified water deliveries to Everglades National Park, Florida. COE, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1993. Central and Southern Florida Project Comprehensive Review Study: Reconnaissance phase plan of study. COE, Jacksonville, Florida.

U.S. District Court. 1991. Settlement Agreement, July 11, 1991. United States of America, et al., plaintiffs, vs. South Florida Water Management District, Florida Department of Environmental Regulation, et al., defendants. Case No. 88-1886-CIV-Hoeveler. Southern District of Florida, Miami.

U.S. Fish and Wildlife Service. 1986. North American waterfowl management plan: a strategy for cooperation. DOI, Washington, D.C.

U.S. Fish and Wildlife Service. 1993. Draft action plan South Florida ecosystem restoration. Prepared for Federal Interagency Task Force on Restoration of South Florida Ecosystems. FWS, Vero Beach, Florida.

U.S. Geological Survey. 1991. Water Resources Data Florida, Volume 2A, South Florida Surface Water. USGS, Miami, Florida.

Vaithiyanathan, P., and C.J. Richardson. In review. Nutrient profiles of the soils and pore waters of the Everglades: comparative study of eutrophic and oligotrophic areas of WCA-2A. Wetlands.

Vymazal, J. 1995. Algae and Element Cycling in Wetlands. Lewis Publishers, Chelsea, Michigan.

Vymazal, J., C.B. Craft, and C.J. Richardson. 1994. Periphyton responses to nitrogen and phosphorus additions in the Florida Everglades. Algological Studies 73:75-97.

Vymazal, J., and C.J. Richardson. 1995. Species composition, biomass, and nutrient content of periphyton in the Florida Everglades. Journal of Phycology 31:343-354.

Walker, W.W. 1991. Water quality trends at inflows to Everglades National Park. Water Resources Bulletin 27(1):59-72.

Waller, B.G. 1976. Analysis of selected benthic communities in Florida Everglades with reference to their physical and chemical environments. USGS, Tallahassee, Florida.

Waller, B.G., and J.E. Earle. 1975. Chemical and biological quality of water in part of the Everglades, Southeastern Florida. USGS.

Walters, C.J., and L.H. Gunderson. 1994. A screening of water policy alternatives for ecological restoration in the Everglades. Pages 757-767 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Walters, C., L. Gunderson, and C.S. Holling. 1992. Experimental policies for water management in the Everglades. Ecological Applications 2(2):189-202.

Ware, F.J., H. Royals, and T. Lange. 1990. Mercury contamination in Florida largemouth bass. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 44:5-12.

White, P.S. 1994. Synthesis: vegetation pattern and process in the Everglades ecosystem. Pages 445-458 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Wiemeyer, S.N., B.M. Mulhern, F.J. Ligas, R.J. Hensel, J.E. Mathisen, F.C. Robards, and S. Postupalsky. 1972. Residues of organochlorine pesticides, polychlorinated biphenyls, and mercury in bald eagle eggs and changes in shell thickness - 1969 and 1970. Pesticides Monitoring Journal 6(1):50-55.

Winger, P.V. 1987. Loxahatchee National Wildlife Refuge: contaminant residues in fish and birds. National Fisheries Contaminant Research Center, Athens Field Station, Athens, Georgia.

Winger, P.V., D.P. Schultz, and W.W. Johnson. 1988. Contaminant residues in fish from national wildlife refuges in the s theast. Pages 38-46 *in* P.J. Stuber, coordinator. Proceedings of the National Symposium on Protection of Wetlands from Agricultural Impacts, Fort Collins, Colorado, April 25-29, 1988. Biological Report 88(16). FWS, Washington, D.C.

Wolff, W.F. 1994. An individual-oriented model of a wading bird nesting colony. Ecological Modelling 72(1994):75-114.

Worth, D.F. 1988. Environmental response of WCA-2A to reduction in regulation schedule and marsh drawdown. SFWMD, West Palm Beach, Florida.

SUBREGIONS 6 and 7:

BIG CYPRESS BASIN AND EVERGLADES NATIONAL PARK (MAINLAND PORTION)

INTRODUCTION

Subregion 6 comprises the Big Cypress watershed north to the Caloosahatchee River watershed and includes the BCNP, Panther NWR, and Fakahatchee Strand State Preserve. Subregion 7 consists of the nonmarine southern Everglades and is coincident with the freshwater and terrestrial portions of ENP and the adjacent authorized East Everglades acquisition lands (Figure 1). Discussion of these two subregions is combined in a single chapter because of their evident ecological connections and similar scientific information needs and restoration objectives. In fact, many of the information needs and objectives apply as well to all hydrologically connected areas in South Florida. Thus, many of the pressing science needs described for Subregions 6 and 7 apply also to Subregion 5 (WCAs).

The approximately 462,000 acres (722 mi^2) of land in South Florida that are considered Indian lands comprise an integral part of the ecosystem. The largest tracts are the Big Cypress Seminole Reservation; the Miccosukee Reservation; the Brighton Seminole Reservation northwest of Lake Okeechobee; and much of WCA 3A, which is perpetually leased by the State of Florida to the Miccosukee Tribe. Since all of the Big Cypress Seminole Reservation and one-third of the Miccosukee Reservation are contained in the BC basin, discussion of scientific information needs for Indian lands is included in this chapter.

The extensive, contiguous areas comprising Subregions 6 and 7 are distinguished by the large proportion of officially designated wilderness area (in ENP) and Federal ownership for controlled-use purposes of most all the area. Thus the ecological problems of the area result primarily, but not wholly, from forces originating outside the subregions. Nevertheless, both the ecological problems and their restoration-related information needs are substantial. Many of the solutions to the problems must necessarily arise from restoration actions applied over the larger regional ecosystem but will be measured within the subregions themselves. Given this situation, the question of scientific information needs was approached in the context of major ecological issues.

MAJOR ISSUES AND INFORMATION NEEDS

The following discussion identifies the major issues and associated science questions and presents related background information and brief statements about current science projects and recommended approaches. The lists of issues and questions are not intended to be exhaustive; rather, the most critical are described. These fundamental concerns, particularly as they relate to the concept of restoration of the regional ecosystem, can be summarized as **the need to understand the nature and implications of ecological change within Subregions 6 and 7**. The changes include all those known or suspected to have occurred in these subregions since the period prior to the earliest organized drainage enterprises of the late 19th century. The major issues in Subregions 6 and 7 are:

- Changes in hydrological cycles.
- Significance of soil changes.
- Changes in water quality.
- Changes in vegetation.
- Decline and alteration of freshwater fish productivity and diversity.
- Declines in aquatic invertebrates.
- Fluctuations in herpetofauna communities.
- Declines in mammals dependent on freshwater marsh habitat.
- Massive declines in wading birds.
- Declines in other waterbirds.

- Decline in numbers and shift in distribution of the American alligator.
- Continuing, possibly accelerating, loss of species from upland communities.
- Quality of surface water entering and leaving Native American lands.

Each issue is addressed below in sections on background, current studies, and critical science questions. Under each question is information on the recommended approach and tasks. The information needs as related to restoration and science objectives for these subregions (based on SSG 1993) are shown in Figure 15.

Changes in Hydrological Cycles

These changes include particularly water levels, surface water inundation, and water flow changes. Key aspects needing critical study relate to alterations of timing of flows and levels into and out of the subregions, and spatial distribution and total volumes of water within and between drainage basins. The effects of variations in meteorological features including annual and seasonal rainfall, storms, and droughts on flow regimes and evapotranspiration patterns need further study and modeling.

Background

Quantitative understanding of declining water levels in the Everglades and BC has only recently been achieved. Historical information on the basins is sparse and mostly anecdotal. The earliest continuous water-level data from the Everglades and BC date from 1952 and 1965, respectively. Early 20th-century drainage operations in the northern Everglades undoubtedly had some effect in the southern Everglades. As development moved south along the Atlantic Coastal Ridge and adjacent lands, drainage was accelerated, first by channelization of coastal rivers and removal of the rapids (e.g., Miami River) and second by dredging and cutting of canals through the Ridge along the entire Lower East Coast (e.g., Snapper Creek, Miami, and New River canals). These projects brought noticeable differences to water levels adjacent to and in the Everglades. Although no continuous record exists to document early declines of water levels, inferences can be made about hydroperiods and hydropatterns by examining physical and ecological data, such as soil descriptions and vegetation community distribution.

Uncontrolled flow to the southern Everglades was impeded by construction of the first east-west road, Tamiami Trail, in 1928. Parker et al. (1955) reported Dade County water levels had dropped by as much as 2 m (6 ft) by 1955. Towards the west and southwest these water-level drops were not as large, but surface water patterns were altered and interrupted. The start of construction for the Eastern Protective Levee system in 1952 reduced flow from the western glades, and construction of large impoundments north of Tamiami Trail in Water Conservation Areas essentially blocked all natural sheetflow into ENP and BC.

Current flow patterns in ENP are limited and controlled by management of the impoundments to the north, extensive agricultural and urban pumping, and drainage canals to the north and east. Unnatural hydroperiods and hydropatterns, as compared to historical hydrologic conditions, are the norm, resulting in sharp reductions of seasonal water levels and large discharges for flood control purposes. Although the BC area initially did not have development pressures as did the eastern Everglades, recent urban and agricultural expansion has caused the lowering of water tables north of the preserve and most likely is affecting water patterns within BC.

Hydrological restoration efforts in the remaining wetlands are dependent on re-establishment of natural hydroperiods and hydropatterns. In order to define what these natural water levels should be, considerable knowledge is requi[illegible]on predrainage and historical hydrology. In addition to developing this fundamental knowledge, impler[illegible]ation of restoration scenarios will require study of hydrological processes. Information is needed to improve the input parameters and databases required for modeling and interpretation.

Spatial aspects require special attention. Ecologically significant and deleterious water-level declines have occurred throughout ENP, particularly along the eastern Park boundary in Northeast Shark Slough, the Rocky Glades, and northern Taylor Slough. In addition, western Shark Slough at times receives large regulatory releases, substantially altering natural water patterns. Areas of short-hydroperiod peripheral wetlands are converted into deeply inundated flowways. Water-level declines in BC originate along the northern boundary and extend southward.

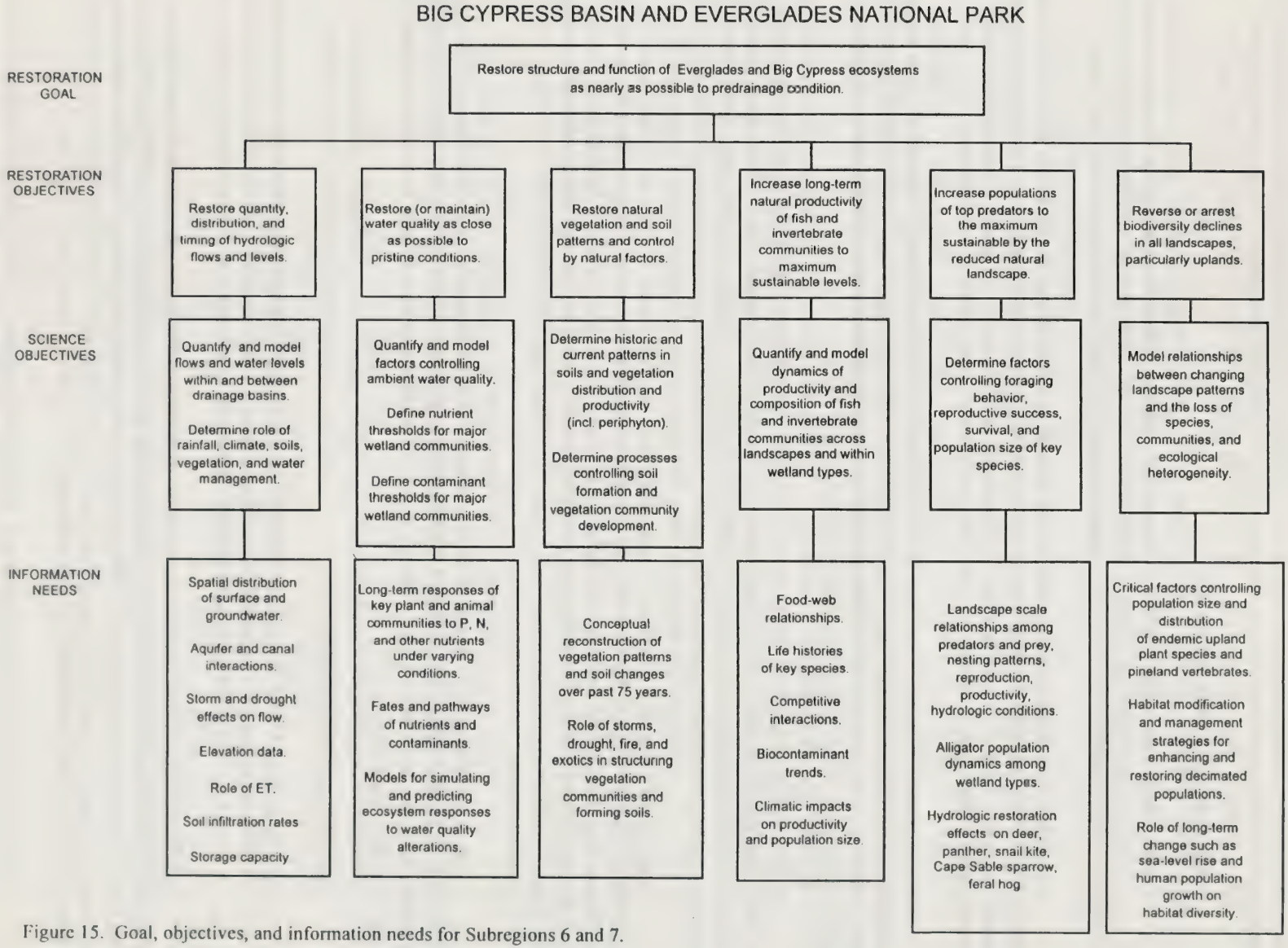

BIG CYPRESS BASIN AND EVERGLADES NATIONAL PARK
RESTORATION GOAL
Restore structure and function of Everglades and Big Cypress ecosystems as nearly as possible to predrainage condition.
RESTORATION OBJECTIVES
Restore quantity, distribution, and timing of hydrologic flows and levels.
Restore (or maintain) water quality as close as possible to pristine conditions.
Restore natural vegetation and soil patterns and control by natural factors.
Increase long-term natural productivity of fish and invertebrate communities to maximum sustainable levels.
Increase populations of top predators to the maximum sustainable by the reduced natural landscape.
Reverse or arrest biodiversity declines in all landscapes, particularly uplands.
SCIENCE OBJECTIVES
Quantify and model flows and water levels within and between drainage basins.
Determine role of rainfall, climate, soils, vegetation, and water management.
Quantify and model factors controlling ambient water quality.
Define nutrient thresholds for major wetland communities.
Define contaminant thresholds for major wetland communities.
Determine historic and current patterns in soils and vegetation distribution and productivity (incl. periphyton).
Determine processes controlling soil formation and vegetation community development.
Quantify and model dynamics of productivity and composition of fish and invertebrate communities across landscapes and within wetland types.
Determine factors controlling foraging behavior, reproductive success, survival, and population size of key species.
Model relationships between changing landscape patterns and the loss of species, communities, and ecological heterogeneity.
INFORMATION NEEDS
Spatial distribution of surface and groundwater.
Aquifer and canal interactions.
Storm and drought effects on flow.
Elevation data.
Role of ET.
Soil infiltration rates
Storage capacity
Long-term responses of key plant and animal communities to P, N, and other nutrients under varying conditions.
Fates and pathways of nutrients and contaminants.
Models for simulating and predicting ecosystem responses to water quality alterations.
Conceptual reconstruction of vegetation patterns and soil changes over past 75 years.
Role of storms, drought, fire, and exotics in structuring vegetation communities and forming soils.
Food-web relationships.
Life histories of key species.
Competitive interactions.
Biocontaminant trends.
Climatic impacts on productivity and population size.
Landscape scale relationships among predators and prey, nesting patterns, reproduction, productivity, hydrologic conditions.
Alligator population dynamics among wetland types.
Hydrologic restoration effects on deer, panther, snail kite, Cape Sable sparrow, feral hog
Critical factors controlling population size and distribution of endemic upland plant species and pineland vertebrates.
Habitat modification and management strategies for enhancing and restoring decimated populations.
Role of long-term change such as sea-level rise and human population growth on habitat diversity.

Figure 15. Goal, objectives, and information needs for Subregions 6 and 7.

Current scientific studies

Several aspects of the hydrology of Subregions 6 and 7 are under active investigation. These projects are summarized below. Extensive monitoring of water levels, rainfall, and surface water inflows also are ongoing. Fifty hydrological monitoring stations are active throughout the freshwater Everglades; 12 are active in BCNP.

Water delivery studies within ENP

Experimental Water Delivery Evaluations. This project will continue assessing the experimental water delivery program and its hydrologic impacts on ENP and adjacent areas. Results will be combined with biological assessments by ENP and NBS staffs, with a report expected in 1996.

Assessment of Changes in Discharges and Resulting Marsh Water Levels in the Lower C-111 Basin in response to the C-111 Interim Project. This project is a continuation of a SFWMD contract, which includes efforts to assess impacts of the C-111 Interim Project on wetlands in the lower C-111 basin. Quarterly and annual reports will be prepared each year.

Management of Water Levels in the C-111 Basin and Urban Runoff Retention. This project is a continuation of a SFWMD contract that focuses on analysis of the operation of the L-31N, L-31W, and C-111 canal systems related to water management improvements to conserve wet-season runoff and improve dry-season water supply. A final project report will be prepared during late FY95.

Taylor Slough Delivery Formula Testing. In 1994 a new rainfall/stage relationship for the Taylor Slough basin was developed based on historical water level and rainfall data from two periods: 1933-1947 and 1970-1981. Follow-up modeling analyses are underway to describe how these formulas should be implemented during future iterations of the experimental program and the impacts that would be expected under these new delivery approaches.

Shark Slough Delivery Formula Development/Testing. This project focuses on development of a revised rainfall-based delivery formula for the Shark Slough basin, which is expected to be completed by late 1995. This new formula would be based on early post-drainage hydrologic data for the Shark Slough basin, as well as the results of Natural System Model simulations. Once the formula is completed, it will require a detailed testing phase using South Florida Water Management Model simulation runs, similar to the formula testing project described above for Taylor Slough.

Shark Slough Modified Water Deliveries Feature Design Memorandum Assessments. This project is performing detailed investigations of the hydraulic design elements and operational criteria for the COE FDMs for the Modified Water Deliveries Project. This project will produce a series of brief summary reports on specific design features of the project.

Numerical modeling studies

Natural System Model Improvements. ENP is continuing work on improvements to the current version of the NSM. Efforts during FY95 focused on development of a 1-mi^2 version of the NSM for applications within the Park. A draft report by ENP hydrology staff is expected in early 1996.

Regional Hydrologic Assessments/Restoration Modeling in the Everglades. Initial assessment of early post-drainage hydrologic conditions throughout the Everglades ecosystem was started by ENP hydrologists in 1990. During FY95, assistance was provided by FIU and South Dakota State University. Results of these investigations need to be combined with detailed analyses of simulations using the 4-mi^2 version of the NSM to develop hydrologic restoration targets for the overall Everglades ecosystem.

C&SF Restudy/South Florida Ecosystem Restoration Support. In 1996, ENP will work with the COE and other cooperators to assess current water management practices in South Florida, document their impacts on the ecosystem, and develop and evaluate needed structural and operational improvements. The work will support the

South Florida Ecosystem Restoration initiative. All of these tasks will require extensive hydrologic modeling efforts using the NSM and SFWMM.

Critical questions and approaches

1. How does the evapotranspiration rate vary across vegetation type and soil type and depths?

This large, but little known, component of the water budget needs to be better defined for use in calibration and verification of models and water budgets.

▸ Set up field measurement stations at six different communities within the freshwater Everglades and BC basin for long-term monitoring of ET.

2. What are the spatial characteristics of the shallow aquifer below the freshwater Everglades and BC basin?

Very little subsurface information exists on the shallow aquifer's depths, transmissivities, and storage coefficients.

▸ Set up a field program to better define these parameters; include test wells and core analysis coupled with surface geophysics for a comprehensive analysis of the subsurface.

3. What are the land elevations in the western sections of the freshwater Everglades and the entire BC basin?

None of the BC basin and only about 50% of the freshwater Everglades have been surveyed. This is a fundamental dataset and is needed for all hydrological and ecological modeling and analysis.

▸ Conventional surveying coupled with testing of remote techniques will be used.

4. What are the overland flow characteristics in wetlands of the freshwater Everglades and BC basin?

In order to quantify wetland flows and freshwater releases to the estuaries, realistic values for the basic parameters relating to flow resistance are needed.

▸ Determine parameters using both laboratory and field experiments.

5. What are the infiltration rates in different soil and vegetation communities of the freshwater Everglades and BC basin?

This parameter is used in water budget calculations and hydrologic modeling and quantifies seepage between surface water and groundwater.

▸ Conduct field studies in areas with different soil characteristics.

6. What are the groundwater seepage rates to the canals and estuaries?

Large seepage flows are known to occur from the natural areas to canals along ENP's eastern boundary and from the canal to natural areas along the northern boundaries of BC and ENP. Also, both surface and groundwater flows to the lower estuaries have not been quantified.

▸ Better define these flows during a long-term field study, using both test wells and flow meters.

7. What are the rainfall/runoff relationships and natural variability of water levels within the freshwater Everglades and BC basin?

To determine operational schemes that promote BC and ENP restoration, relationships between stages, flows, and rainfall need to be established to guide water managers.

- Using physically based and statistical models, refine, develop, and evaluate formulas to guide water deliveries to the natural areas.

8. What are the predrainage hydroperiods and hydropatterns within the freshwater Everglades and BC basin?

This information is needed to guide the restoration effort. Comparisons can be made between predrainage and drainage periods to evaluate natural spatial and temporal water distributions within a reduced Everglades.

- Conduct critically needed analysis of data from Fakahatchee Strand State Preserve, where staff have monitored flows and levels at numerous stations throughout the preserve since 1983.

- Using historical information and models, develop and analyze predrainage relationships.

Significance of Soil Changes for Hydrological and Biological Restoration

Background

Evidence indicates that artificial drainage of the greater Everglades and associated urban and agricultural development have caused changes in the soils of the Everglades region. The most widespread effect appears to be loss of surficial organic soils in freshwater marshes as a result of accelerated oxidation of soil organic matter because of lowered surface and groundwater levels (Craighead 1971). A second important loss of organic soils is traceable to wildfire, which is believed to be more severe and widespread as a result of artificial drainage but also varies considerably in spatial extent and severity as a consequence of droughts (Craighead 1971).

Soil formation rates are little known for the marl and peat types in the subregions, but are relatively high for peat and low for marl. The qualitative role of vegetation (in the form of arboreal, macrophyte, or periphyton) in forming the broad soil types is generally known, but how and why the rates differ are not. In coastal areas, strong hurricanes move large quantities of sediments, reshaping ground elevations, creating or destroying natural levees, and otherwise modifying topography (H. Wanless, pers. comm.). Most hurricane effects occur in the marine-influenced zone, which is not included in Subregions 6 and 7. Such episodic processes, however, do influence vegetation development and local hydrology, and therefore animal habitat, over extensive coastal areas that extend into the freshwater Everglades. A well-known example involves transport of mangrove propagules into freshwater marsh areas where development of vegetation communities best characterized as mangrove scrub-wet prairie (or marsh) has occurred over thousands of hectares. Eventually this process, along with expansion of mangroves along freshwater tributaries in Shark Slough, can be expected to modify soil-forming processes.

In the larger system context, overall soil mass influences hydrologic dynamics of the Everglades in several ways. By mantling the limestone substrate with varying depths of sediment accumulation, local topography is modified. Variations in topography, in turn, influence sheetflow dynamics, groundwater recharge, and seasonality of flows and hydroperiods, thus helping define wetland hydrological characteristics. Soils also contribute to the timing and storage components of the water budget through such properties as hydraulic conductivity rate and water retention capacity. Deep peat deposits, for example, store water long after precipitation events, thus mediating a gradual, lagged release of water long after the cessation of the wet season. In this sense, an intact regional soil mass played a vital role in determining the characteristic timing of marsh flows and levels.

On a more local scale, distribution and depth of peat and marl soils and associated vegetation types (including periphyton) structure habitat for terrestrial and aquatic animals. Changes in soils, whether natural or man-caused, alter this function, creating new vegetation types and related animal communities. As an example, burn-out

of peat deposits in tree islands converts arboreal vegetation to herbaceous marsh, willow-heads, or shrub stands depending on elevation and depth of burn-out (Wade et al. 1980). Loss of surficial peat deposits from chronic overdrainage also affects aquatic food chains through reduction of the herbivorous food base. Local populations of many species are thus affected by organic soil losses, including tree snails, wading birds, and alligators.

Spatially, most known or suspected soil changes have occurred in Subregion 7, particularly in the Northeast Shark Slough area, Rocky Glades, and adjacent Taylor Slough. Reduction in peat depths also seems likely in Shark Slough proper, but little evidence is available for drawing conclusions as to the extent of losses. Alteration of deposits related to hurricanes would be expected on the mainland north of Florida Bay, on Cape Sable, and along the Gulf Coast. Note also that major changes in soils probably have occurred in the adjacent WCAs with consequences for hydrology and habitat in Subregions 6 and 7.

Current scientific studies

Little work on soils is being conducted in the subregions, except that incidental to other topics such as mercury accumulation in sediments. The Center for Climate Research of the University of Wisconsin is, however, engaged in analysis of sediment cores taken from a wide area that includes WCA 3, ENP, and the Florida Keys. The study's purpose is to reconstruct historic vegetation patterns and infer hydrologic conditions from paleoecological materials. Results are expected in late 1995.

Critical questions and approaches

1. What are the modern (and what were the historic) formation rates of major soil types and the critical hydrologic and vegetation factors determining those rates?

- Estimate past formation rates from isotope activity profiles.
- Estimate present and future rates by creating marker horizons or other procedures for measuring accretion of soil materials in major ecosystem types in Subregions 6 and 7.

2. Over what area have soils been altered as a direct and indirect result of overdrainage?

- Complete modern soil survey across Subregions 6 and 7 and compare results with past surveys.
- Combine with survey data from adjacent areas.
- Include estimates of hydraulic properties, total mass and volume, state of decomposition, and related characteristics in relation to spatial pattern.

3. Within the major basins that have experienced alterations, what are the estimated volumes (area and depth) of soil losses and how has local topography been affected?

- Use historical dating of sediments to reconstruct soil depth profiles and determine age of surficial layers.
- Compare present soil composition and depth to predicted soil composition as inferred from vegetation pattern.

4. How have the relationships between vegetation and soil types changed since predrainage times?

- Develop a model of landscape vegetation-soil dynamics that allows for hindcasting of soil formation dynamics from historic vegetation data. Include treatment of periphyton-mediated calcite formation and marl soil formation, particularly how these processes vary with changes in periphyton composition and mass.

5. What is the significance of soil changes for sheetflow and groundwater recharge?

- Simulate hydrology of selected sub-basins within the subregions, incorporating explicit simulation of soils based on measurements of soil physical and chemical properties.

6. What are the physical and chemical controls on periphyton as an agent of calcite accumulation and marl soil formation? How do these processes vary spatially and temporally across ecosystem types in the two subregions?

The key need is to quantify the importance of biological, chemical, and physical factors in controlling the role of periphyton in marl formation over a range of climatic, water quality, and habitat conditions. (Note that some of the work could be combined with related work described below in section on vegetation changes.)

- Conduct extensive field studies of periphyton growth and development trends.
- Combine field results with data on chemical and physical characteristics of the sampling sites.
- Repeat sampling over a number of years to encompass variations in climate.
- Verify inferences with controlled mesocosm studies.

Changes in Water Quality

Background

The historic Everglades was a hardwater, oligotrophic system depending primarily upon rainfall for nutrients. Flows from Lake Okeechobee periodically augmented the northern Everglades' supply of nutrients, suspended organic particles, dissolved organics, and other materials. At present, the Everglades is subject to intense disruptions of geochemical processes due to human activities along its margins and to some extent from atmospheric transport processes. With the advent of intense land use change, notably artificial drainage and cultivation within the EAA and development of the Atlantic Coastal Ridge, phosphorus and other substances are delivered to the Everglades in quantities significantly above historic levels. One consequence of such enrichment can be understood from the extensive development of cattail stands in phosphorus-enriched areas formerly dominated by sawgrass (Doren et al. 1995).

The Everglades is protected by, among other standards (including nondegradation standards), Florida's Class III narrative nutrient standard. This standard requires that nutrient additions shall not be permitted at levels which cause an imbalance in fauna or flora. Present technology to treat agricultural runoff, the primary source of excess phosphorus currently reaching the Everglades in large amounts, is expensive and untried in the oligotrophic range for phosphorus. Thus there is great interest in determining the "threshold" value which, when adopted, will represent a maximum concentration which can be delivered without harm to natural communities of the Everglades.

The agricultural industry has supported studies to determine nutrient thresholds through field dosing approaches in WCA 2B. The State of Florida supports transect and field mesocosm studies, rather than controlled dosing in channels. However, many scientists believe that direct application of nutrients under controlled hydroperiods will be necessary to determine a protective phosphorus standard. A program undertaken by FIU with Federal support is focusing on this approach. The FDEP will make the final determination of the standard through administrative procedures established to report a protective standard by 2001.

Current scientific studies

The sole science activity in the two subregions is a field-intensive, multichannel dosing study being conducted by FIU scientists in the freshwater Everglades of Shark Slough within ENP. The project is presently underway and will continue for several more years. Results are expected to satisfy administrative needs to determine

a field threshold for phosphorus effects in the freshwater Everglades and provide much basic data on nutrient dynamics and ecological effects.

Critical questions and approaches

1. What levels of biogeochemical disturbance are compatible with restoration and preservation of a viable Everglades system?

Estimates for the Everglades system of rates of influx, storage, recycling, and loss of major nutrients and toxic substances are fundamentally important.

- Construct mass balance models from available information as a first step. More refined models requiring new data gathering efforts can then be prescribed and assembled.

- Simultaneously initiate finer scale models of process dynamics for phosphorus, nitrogen, and selected ions (including mercury) to refine internal cycling relationships, including dynamics of movement and accumulation in the food web.

- Dedicate special emphasis in both large-scale mass-balance models and fine-scale internal process investigations to the role of organics, both dissolved and particulate, in evaluation of natural and anthropogenically derived fluxes of materials in the modern Everglades.

2. What is the threshold value for total phosphorus in waters that can be released into the Everglades system from the EAA, Atlantic Coastal Ridge urban development, and southeastern catchment basin?

- Develop an experimental design with adequate statistical power and reliable technology to provide accurate concentrations and flow measurements under rigorous field conditions.

- Implement the design in appropriate areas of the Everglades system, and collect a minimum of 3 years of field data.

3. What sources, modes of transport, interaction with organic matter, and sinks exist for pesticides used on the periphery of the Everglades? What are the pathways for bioaccumulation into the Everglades food web? What additional monitoring of these phenomena is necessary?

Much of the current monitoring for pesticides may detect some of the compounds because they are bound to the high organic content of inflows to the Everglades.

- Conduct additional studies to determine the compounds currently in use, timing of usage, and interactions likely to occur within the water column and sediments. Small-scale field and laboratory projects are required.

4. What are the full effects of water quality decline on plant and animal communities of the Everglades?

A great deal of new scientific study has been initiated by the recent litigation. Follow-up studies that replicate sampling of water quality and plant responses along transects in the WCAs and ENP are needed to document future trends. The following tasks are particularly needed:

- Conduct replicated field studies of community and species functions and properties from sites located along transects that are accurately characterized as to sediment, water column, detritus, and biomass content of nitrogen and phosphorus.

- Conduct mesocosm and laboratory studies of the effects of nutrient additions and changing ratios upon periphyton, macrophytes, decomposers, and short-lived consumers.

Changes in Vegetation

Background

The vegetation of Subregions 6 and 7 is controlled to a large degree by a few interrelated factors, including elevation, substrate characteristics, hydroperiod, water depths, and several aspects of fire (Craighead 1971; Duever 1984; Robertson 1955; Wade et al. 1980). Disturbances such as freezes (Olmsted et al. 1993), hurricanes (Armentano et al. 1995), droughts (Craighead 1971) and nutrient enrichment (Doren et al. 1995) also play a role in determining vegetation structure and function. Human-induced changes such as modification of hydrology, altered fire regime, loss of organic soils and invasion of exotic pest plants have caused both obvious and subtle changes in vegetation (Alexander and Crook 1984; Ewel 1986; Kolopinski and Higer 1969). Distinguishing natural from anthropogenic sources of vegetation change is important for evaluating restoration success. Although vegetation in Subregions 6 and 7 for the most part is relatively little altered compared to other subregions, evidence suggests that important components of the freshwater and terrestrial vegetation, especially in Subregion 7 but also to some extent in Subregion 6, are in disequilibrium with respect to present hydrology, soils, and fire regime.

Numerous general descriptions of vegetation in ENP and BC exist. The report and map of Davis (1943) present a comprehensive overview of South Florida vegetation. BC vegetation was mapped by McPherson (1973), and a map based on interpretation of 1984 photography exists in digital GIS format. Currently the University of Georgia is developing a detailed vegetation map of ENP, BC, and BNP that would be the first detailed map of the combined area. Several relatively small-scale vegetation maps have already been completed for selected areas of ENP and BC (e.g. Gunderson and Loope 1982a,b; Olmsted et al. 1980). Unfortunately, there is no systematic program to monitor vegetation in ENP and BC. However, a systematic effort to locate original sampling points from some earlier studies (e.g., Olmsted et al. 1980) has begun within ENP (T. Armentano, pers. comm.). For other early studies, however, such as those of Craighead, precise sampling locations for landmark field work on vegetation communities are unlikely to be found. Few permanent plots exist, and those that do are neither well documented nor routinely sampled. However, a series of aerial photographs exists for most of the area dating back 30 years or more. Changes in physiognomy over the last few decades can be detected by comparing remote imagery, but more subtle changes in species composition, which may reflect important underlying changes in environmental conditions, cannot.

A general appreciation has been gained of the rich plant species diversity and distinctive flora of the area, including the unique intermixing of West Indian and temperate elements and the high degree of endemism (Avery and Loope 1980; Snyder et al. 1990). About 9% of South Florida vascular flora are endemic to the Region, with endemism concentrated in the uplands. Many of these species are being subjected to intensive development pressure, and some no doubt cannot be saved despite heroic efforts by state, local, and Federal agencies. Relatively few resources are being allocated to investigations that could provide information critical to saving some populations, thereby maximizing the probability of sustaining them well into the future. In many cases, the present status of endemic and nonendemic, but rare or endangered, species is not known.

Current scientific studies

Much of the previous vegetation work in Subregions 6 and 7 is related to exotic plants (e.g., Ewel et al. 1982; Myers 1983; Loope and Dunevitz 1981) or fire (e.g., Herndon and Taylor 1986; Hofstetter 1984; Snyder 1986). Current studies concentrate on impacts of Hurricane Andrew on the structure of forested communities: mangroves, hammocks, and pinelands. Table 6 summarizes all currently active hurricane response studies. Note that the entire NPS program is presented, including studies in coastal areas that fall within Subregion 8.

Results of a rapid survey of immediate hurricane effects on aquatic, marine, and upland systems in the three South Florida mainland NPS sites were published in a special issue of BioScience (Loope et al. 1994; Pimm et al. 1994; Roman et al. 1994; Smith et al. 1994; Tilmant et al. 1994). More detailed information on residual effects in the years following the storm is being collected and analyzed. Several reports have been submitted or are in preparation. The effects on forests as of 2 years after the storm are summarized in Armentano et al. (1995).

Table 6. Science projects funded by the NPS Hurricane Andrew Program (1993-96). The following projects address hurricane effects and response processes for specific ecosystems in areas crossed by Hurricane Andrew.

Investigator	Topic	Institution	Funding Instrument or Type
Oberbauer & Koptur	Responses of Four Nontidal Forests Types	FIU	CPSU
Slater & Platt	Hardwood Hammocks of Long Pine Key	LSU	Suppl.
Platt	Slash Pine Forest Structure & Demography	LSU	Suppl.
Ross & Meeder	Rare Plants in Pine Rocklands	FIU	CPSU
Snyder & Koptur	Plant Response to Fire in Pinelands	BCNP	CPSU
Hartman	Exotic Spread & Invasibility: *Schinus* and *Melaleuca*	Rutgers Univ.	New
Trexler	Structure & Function of Freshwater Aquatic Communities	FIU	CPSU
McKenna	Fish Community Effects in Mangrove Habitats	FDNR	New
Welch	Vegetation Map/Digital Database: ENP, BCNP, BNP	Univ. Georgia	New
Sparks & Bennetts	Effects on Tree Snails	BCNP	New
Robson	Effects on Short-tailed Hawk Status	FGFWFC	New
Emmel	Effects on Schaus' Swallowtail	UF	New
Szmant	Effects on BNP Coral Reefs	UM	CPSU
Jones	Water Quality & Biochemistry in Coastal Areas	FIU	Suppl.
Wiebe	Nutrient Fluxes-Algal Mats, Mangrove & Seagrass on Gulf Coast	Univ. Georgia	New
Wanless & Tedesco	Sediment Redistribution & Deposition	UM	CPSU
T. Smith	Effects on Structure & Function of Gulf Coast Mangroves	FDNR	New
Twilley	Resource Utilization in Gulf Mangrove Communities	Univ. SW Louisiana	New
Robertson	Bald Eagle - Osprey Census	ENP/BNP/BCNP	ENP
Meyer & Robertson	Pineland Bird Survey Declines & Extirpation	BCNP/ENP	ENP
Bass	Cape Sable Sparrow Census	ENP/BCNP	FWS support
Jansen	Red-cockaded Woodpecker	BCNP	BCNP

Critical questions and approaches

1. What changes have occurred in the South Florida vegetation pattern since the predrainage era? How can we detect future changes?

- Conduct paleolimnological studies of Deep Lake and other similar features to document changes over the last few thousand years.

- Using available imagery and field data, document changes that have occurred over the last several decades.

- Develop a comprehensive vegetation monitoring program using a combination of remotely sensed imagery and permanent plots.

2. What have been the environmental factors responsible for observed changes in vegetation structure (including periphyton)? What is the relative importance of the different factors in causing change?

- Conduct field experiments that include manipulation of suspected factors, including hydroperiod, water depth, water quality, substrate, and fire.

- Develop a process model of vegetation development for selected major vegetation types based on results of field experiments and relationships of vegetation pattern to site characteristics at a large number of sites.

- Conduct extensive field surveys of periphyton accumulation and biological and chemical composition in all habitat types in which it occurs. Repeat the surveys at least annually, but seasonally for selected sites, and relate to hydrological and water quality parameters.

- Develop a predictive model of periphyton dynamics that is driven by hydrological, soil, and water quality parameters.

3. Within areas where a given vegetation cover type has persisted since the predrainage era, what changes have occurred in composition and productivity?

- Within major vegetation types, measure accumulated standing crops and estimate present rates of primary production using standard harvest methods and repeated sampling appropriate to habitat and vegetation type.

- Compare areas differing in present condition and recent history (e.g., in sawgrass stands, select sites of known fire histories and those subject to sawgrass decline and altered flooding regime; include dense and sparse stands).

- Conduct sampling at sites with well-documented soils, topography, and hydrologic characteristics.

- Begin developing a stand development or growth model driven by the main abiotic forces. This model should be constructed to receive hydrologic inputs and treat stochastic events such as fires and freezes.

4. To what extent is plant succession a factor in determining vegetation composition and development?

- Reconstruct historical patterns based on archival information.

- Determine fire, hurricane, and freeze chronologies for documented sites.

- Review botanical literature from other hurricane-prone regions.

- Establish temporal trends for selected sites using earlier studies (including Hurricane Andrew plots) and archived information.

- Continue plot analysis where plot locations from past studies can be determined.

- Establish a permanent plot network with standardized sampling to evaluate future trends.

5. What is the status of special (rare or listed) plant populations? How can long-term survival of these populations be assured?

- Design and implement a monitoring program for populations of special plant species.

- For species suspected to be in decline, conduct detailed studies of population dynamics, including manipulative experiments, if necessary as an approach to understanding causative factors.

6. To what extent have exotic species disrupted natural community function and what needs to be done to minimize these effects? What exotic species may pose problems in the future?

- For the area as a whole and for sites differing in extent of invasion, determine through field studies how community characteristics have been altered.

- Improve control strategies for known problem species through integrated use of herbicides, biological control, and mechanical control including fire.

- Develop autecological profiles for anticipated problem species; e.g., *Neyraudia reynaudiana* and *Rhodomyrtus tomentosus*.

7. What is the role of periphyton in aquatic food-chain support and in structuring habitat for various trophic levels from microbes to small predators? Related questions about periphyton function are covered above in sections on soils and water quality.

- Conduct field, laboratory, and mesocosm studies of periphyton utilization by herbivorous and detritus-feeding fish and invertebrates.

- Determine through field and mesocosm studies how uptake and food-chain transfers vary with habitat, soil type, and hydrology.

- Conduct field studies to investigate how periphyton accumulation serves as habitat and refugia for various organism and alters microenvironments.

- In related work, investigate transfer of soil-generated nutrients into aquatic food chains. (Some of this work is proposed above in the water quality section.)

Decline and Alteration of Freshwater Fish Productivity and Diversity

Background

In the Everglades and BC wetland systems, natural environmental conditions regularly vary seasonally, annually, or on a multiannual basis. The effects of routine environmental variability on aquatic animals are compounded by stochastic events like hurricanes and severe fires. Aquatic animals have various means to cope with environmental variability. These include movements among habitats to find breeding sites or refuge from drying, resting stages to survive drought, reproductive adaptations, etc. Human-induced changes have affected the natural variability of environmental conditions by altering seasonality and areal extent of flooding in wetlands, drainage or flooding of neighboring marsh systems, and pollution from urban and agricultural areas (Gunderson and Loftus 1993). Aquatic communities respond to human-induced changes through loss of diversity, changes in composition and abundance, and probably through alterations in energy-flow pathways (Loftus et al. 1990). Some of the changes are subtle and difficult to detect in the early stages until they are manifested in obvious collapses of native communities and natural processes. A good example is the recent finding of mercury at dangerous levels in fishes

of this region and their predators (Loftus and Bass 1992). As human population pressures on wetland systems increase, it is crucial to have adequate information to distinguish natural variations in environmental factors and community responses from those produced by human interference. Changes that reduce population sizes, community composition, or availability of aquatic animals will affect all facets of the ecology of these wetlands.

To ensure healthy aquatic ecosystems and detect natural or human-induced changes in those systems, baseline data on constituent aquatic communities and their ecology are required. Because the Everglades/BC system is composed mainly of aquatic habitats, knowledge about fishes is especially important. Yet fishes are difficult to study because of sampling and transportation logistics and wide, natural variability in populations and environmental conditions. Collection of baseline data to document fish community composition, ecology, and dynamics has not always received emphasis or support because it is expensive and long term and because fishes are not as charismatic as other fauna. However, fishes support many of the predatory animals, especially alligators and wading birds, that characterize the Everglades/BC marshes. Fishes testify to the health of the wetlands and attract human visitors, from fishermen to naturalists. It is important to catalog the fish faunas and to understand their productivity and availability to predators under natural conditions.

Because of hydrological changes wrought by drainage and impoundment and the loss of spatial extent and functioning of former wetlands to development (Gunderson and Loftus 1993), there can be little doubt that fish standing crops and overall numbers have declined. These changes to the original system have also altered the timing and areas of fish availability to predators. Indirectly, fishes have been detrimentally impacted by hydropattern alteration through effects on alligators, which prey on fishes and provide them dry-season refuge in their ponds, and through impacts on wading birds, which transfer energy from the marshes to other habitats through predation.

Non-native fishes have colonized natural and disturbed habitats during the past three decades. The climate and geography of the subregions make them conducive to non-native animal invasions (Loftus and Kushlan 1987). The rate at which fishes have been introduced into area waters has increased since the mid-1970s. Documented impacts on native animals include predation, nest-site competition, and habitat disturbance (Loftus 1988). The eventual extent of invasion, geographically and numerically, is uncertain. It seems likely more species will invade and all will extend their ranges within the subregions, with unknown ecological consequences. Non-native fishes may divert food-web energy into biomass unavailable to top-level predators.

The first studies of southern Florida freshwater fishes were done by the UM in the early 1950s-1960s (Hunt 1952; Reark 1961). Those mostly unpublished studies provided some data on species composition, diets, standing stocks, and habitat use. From 1965-1972, the USGS was contracted to collect data on fish community composition and population variability in Shark Slough (Kolipinski and Higer 1969); those data were published later (Kushlan 1980). In 1976, the Research Division of ENP began a long-term commitment to studying the aquatic ecosystem. The inventory data for fishes in the southern Everglades are current and accurate. Some level of information exists for fish habitat usage, food habits, reproduction, standing stock dynamics, and relation to hydropattern; however, many of those studies were preliminary rather than definitive in nature.

Current scientific studies

Recent investigations include studies of the effects of hydroperiod alteration on marsh food webs (Loftus et al. 1990) and effects of Hurricane Andrew on the community (Roman et al. 1994). A long-term study of effects of natural and altered hydropatterns on aquatic animal community structure and standing stocks in several Everglades marshes is continuing and has been expanded. In the BC region, little work has been done with fishes. Kushlan (1974) reported responses of fishes to dry-season conditions in an alligator pond. There are distributional data for native and exotic fishes from U.S. 41 and southward in the Preserve (Loftus and Kushlan 1987). Limited, quantitative community data exist from Corkscrew Swamp (Carlson and Duever 1977) and the southern BC region (Carter et al. 1973). Since 1990, the FGFWFC has sampled game fishes in this subregion for mercury concentrations.

Freshwater fish and aquatic invertebrates are sampled regularly in Shark River Slough. Throw traps are used at nine sites five times yearly, continuing a database begun in 1977. Electrofishing in five alligator ponds is

done twice a year and, for qualitative purposes, pull traps continue to be employed to sample aquatic animals in the slough.

Critical questions and approaches

1. What is the relationship between function and organization of fish communities, particularly in under-sampled habitats?

► Support a data collection effort throughout both subregions for a minimum of 5 years to try to encompass a range of climatic conditions. Focus efforts on the Big Cypress Swamp, freshwater-mangrove interface, and short-hydroperiod peripheral wetlands. Match methods and sampling frequency to the current collection program in ENP for comparability.

► Link data collection in Subregions 6 and 7 with that in adjacent regions to provide system-wide monitoring of fish numbers and to take advantage of the large, natural "experiment" to assess fish responses to conditions resulting from drainage and impoundment of waters in various compartments of the Everglades.

2. For important fish species what are the key life-history parameters?

Although some information on reproductive aspects, recruitment seasons, and age and growth have been collected, the database is far from complete. The tasks below, in combination with data from Question 1 above, would provide the information needed to construct life tables for the species under different conditions in the system.

► Analyze fish otoliths for daily growth increments to calculate age at size as well as to estimate growth rates under different seasons and habitats.

► Conduct a study of fish fecundity and related parameters to estimate reproductive potential.

3. What are the food-web relationships of fishes of the Everglades/BC system?

Unraveling the connections and calculating flow networks will be valuable to understanding ecosystem function.

► Carry out direct observations of fish gut contents and feeding behaviors.

► Conduct stable isotope analysis of fish tissues to determine which plant groups are the primary carbon sources for fishes in different habitats. This type of study is also useful in predicting passage of biocontaminants through the system.

4. What are the ranges, composition, and abundance of non-native fishes in the Everglades/BC system?

► Conduct periodic and well-planned monitoring of habitats not covered by other fish sampling studies. Some of the needed information would be gathered in tasks under Question 1, in addition to interaction studies discussed under Question 7 below, however more extensive sampling will be required to fully understand the non-native fish problem.

► Investigate potential control methods. Control possibilities will have to be tied to life-history studies to identify vulnerable life stages or behaviors that can be targeted.

5. What are the trends in biocontaminant levels of the fishes?

► Conduct periodic screening for contaminants to detect potential problems. Fishes are integrators of contaminants in their environment, so are effective early-warning species for contaminant detection.

▸ Conduct studies of mercury mobilization, transfer, and direct effects on fish health and behavior. The mercury issue is a currently recognized problem with implications for the entire system.

6. What are the landscape-level parameters necessary to understand fish population dynamics?

Attempts to build credible and useful simulation models for fishes in Everglades/BC are underway but are limited by lack of important data. The studies needed to provide those data include those above on reproduction, recruitment, age, growth, and mortality and also several landscape-based studies, including:

▸ Determine the dynamics of fish movements related to seasonal fluctuations in water level, including composition and numbers in refugia during the dry season, distances and rates of seasonal dispersal movements, etc. Although some information may be gathered through traditional mark-recapture study, the small sizes of the fishes and vast area of the two subregions generally preclude that approach. An indirect way to obtain these data is to use genetic markers to identify population structure, which may provide a gauge of the degree of mixing of fish populations via dispersal movements.

▸ Develop a trophic-network model of the fish community, which will provide a "circuit diagram" of the pathways and amounts of energy flow and compartmentalization. This modeling approach is a useful diagnostic tool in system analysis and also has value in tracking movement of contaminants through the food web. There is a possibility of integrating this kind of model with simulation models to yield a dynamic picture of how changes in the environment translate into community changes and thence into food-web shifts. Construction of a trophic network requires better data for fish-prey population biomass and cycling than is now available.

7. What are the key community behavioral and competitive relationships among fishes?

Some studies needed to understand the fish community are difficult to carry out in the field, yet require more space than the confines of laboratory aquaria. Construction of an experimental mesocosm is planned in ENP to meet the needs of scientific investigations.

▸ Conduct mesocosm studies on predator-prey, competitive, and indirect interactions.

▸ Conduct mesocosm studies on the role of nutrient inputs into the Everglades in causing shifts in marsh food webs.

▸ Conduct mesocosm studies to examine interactions between introduced and native fish and to test potential control methods.

Declines in Aquatic Invertebrates

Background

Freshwater invertebrates are important and abundant animals in the Everglades/BC system and, as such, are critical in transfer of energy through the system, particularly in the shorter hydroperiod wetlands. These animals operate at several trophic levels in the wetlands, as primary consumers of plant material and detritus to carnivores and scavengers. Some species, such as the crayfish and apple snail, are major prey for fishes and other predatory species, including characteristic or endangered animals like the snail kite, white ibis, and American alligator. Factors that influence invertebrate numbers, biomass, and composition therefore affect energy flow through the wetlands. The ecology and life histories of invertebrates are intimately tied to hydrology of the marsh, which is determined mainly by rainfall but increasingly by water-management practices. Water management through flood releases, diversions, and impoundment of water appears to adversely affect aquatic invertebrate stocks and their distributions. Such direct effects of water management are compounded by the subtle impacts of drying on marsh ecology, in particular reduction of wetland productivity. Disturbances, such as hurricanes and droughts, result in dramatically reduced standing stocks, sometimes for years following the event.

Two of the first studies to report invertebrate data from Subregions 6 and 7 were done by the UM (Hunt 1952; Reark 1961). From 1965-1972, the USGS collected data on densities and biomass of some macroinvertebrate species in Shark Slough; those data were published in a series of papers (Kushlan 1975; Kushlan and Kushlan 1979, 1980b). In 1976, ENP began to support studies of habitat use, reproductive seasonality, and standing stocks for selected macroinvertebrates, as part of fish investigations in the Everglades. Baseline compositional data for certain groups of aquatic insects and snails published in statewide treatments are applicable to the two subregions. Recent investigations provided the first information on microinvertebrate composition and dynamics (Loftus et al. 1990; Reid 1992). For most freshwater invertebrates, baseline data on population levels and dynamics are limited to only the most abundant groups (cladocerans, copepods, and some aquatic insects) and apply to only one habitat type. Data for the apple snail (*Pomacea paludosa*) (Kushlan 1975), crayfish (*Procambarus alleni*) (Kushlan and Kushlan 1979), and freshwater prawn (*Palaemonetes paludosus*) (Kushlan and Kushlan 1980b) have been published. Non-native invertebrates are less well inventoried in the subregions because of sampling and identification difficulties; data on composition, distribution, and habitat usage are available for some taxa of molluscs and dragonflies.

Most of the data for invertebrates in Subregions 6 and 7 have been collected from the Shark River Slough in ENP. A small amount of density and biomass information, mainly for larger macroinvertebrates, has been collected from Taylor Slough, the Rocky Glades, and the marsh-mangrove interface. There are almost no quantitative data for western Shark River Slough or the Big Cypress Swamp. A very limited database on reproduction, diet, size frequencies, growth, and other important life-history characteristics exists for a small study area of long-hydroperiod marsh in central Shark River Slough. Any invertebrate study should attempt to collect data in representative habitats across the subregions, in light of the poor state of knowledge.

Current scientific studies

The only invertebrate sampling is in Shark River Slough as part of the fish study described above.

Critical questions and approaches

1. What are the functional dynamics of the invertebrate community throughout the Everglades/BC system?

The studies below address several objectives and would provide data for model building, calibration, and validation.

- Complete baseline inventories of invertebrate communities in representative habitats to estimate species richness and catalog the fauna. Too little is known about most invertebrate taxa in Subregions 6 and 7 to determine whether threatened and endangered species occur.

- Collect data on invertebrate community composition and dynamics throughout both subregions to understand the functioning and organization of communities, especially in short-hydroperiod peripheral wetlands where crayfish appear to be the dominant aquatic species. Match methods and sampling frequency to the current collection program in ENP for comparability. The effort should be supported for a minimum of 3 years to try to encompass a range of climatic conditions and to use the large, natural "experiment" of the divided Everglades to assess responses to environmental conditions.

2. What are the key life-history parameters of important macroinvertebrate species?

Life-history parameters should be studied at sites that represent a range of subregion environments. Although information on reproductive aspects, recruitment seasons, and growth has been collected for some species, the database is far from complete. These data are needed to meet several objectives. The tasks below, in combination with data from Question 1, would provide the information needed to construct life tables for the species under different conditions in the system.

- Conduct a study of size frequencies and markers to estimate growth rates in different seasons and habitats.

▸ Conduct a study of fecundity and related parameters to estimate reproductive potential.

3. What are the key food-web linkages involving aquatic invertebrates in Subregions 6 and 7?

Unraveling the connections and calculating the flow networks will be valuable to understanding ecosystem function.

▸ Carry out direct observations of invertebrate gut contents and feeding behaviors.

▸ Conduct stable isotope analysis of invertebrate tissues to determine which plant groups are the primary carbon sources. This type of study is also useful in predicting passage of biocontaminants through the system.

4. What are the changes in range, composition, and abundance of non-native invertebrate species in the Everglades/BC system?

▸ Conduct periodic and well-planned monitoring of habitats not covered by other field sampling studies. Some of the needed information would be gathered in tasks under Question 1, in addition to interaction studies discussed under Question 7 below, however more extensive sampling will be required to fully understand the non-native invertebrate problem.

▸ Investigate potential control methods. Control possibilities will have to be tied to life-history studies to identify vulnerable life stages or behaviors that can be targeted.

5. What are the biocontaminant loading problems and contaminant effects on population dynamics and health of invertebrates in the Everglades/BC system?

▸ Conduct periodic screening for contaminants to detect potential problems. Like fishes, invertebrates are integrators of contaminants in their environment so are effective early-warning species for contaminant detection.

▸ Conduct studies of mercury mobilization, transfer, and direct effects on invertebrates. The mercury issue is a currently recognized problem with implications for the entire system.

6. What are the landscape-level dynamics of key invertebrates in these subregions?

Simulation models for invertebrates are presently being constructed but are hampered by lack of data. Basic information is unavailable to describe the ecological processes that regulate and structure invertebrate communities in different habitats. This information is critical to the simulation modeling process used to evaluate ecological impacts and to selection of alternative management options to restore the system. The studies needed to provide those data include those above on reproduction, recruitment, age, growth, and mortality and also several landscape-based studies, including the following:

▸ Determine the dynamics of habitat use, movements, and dispersal among habitats related to seasonal fluctuations in water level and other environmental conditions. This would include composition and numbers in refugia during the dry season, diapausing ability, distances and rates of seasonal dispersal movements, etc. Although some information for larger invertebrates may be gathered through traditional mark-recapture study, that approach is infeasible for most species. An indirect way to investigate these questions is to use genetic markers to identify population structure, which may help determine the degree of mixing of populations as it relates to dispersal movements.

▸ Document the ecology and composition of invertebrates that permanently occupy, or show dry-season use of, subterranean aquatic habitats and their ecological interactions with surface-water environments.

▸ Develop a trophic-level model of the invertebrate community, based on linkages found in Question 3. This will provide a diagnostic tool to discern pathways and amounts of energy flow and compartmentalization and also to track movement of contaminants through the food web. There is a possibility of integrating this kind of model with simulation models to yield a dynamic picture of how changes in the environment translate into community changes and thence into food-web shifts. Construction of a trophic network requires better data for invertebrate community biomass and cycling than is now available.

▸ Determine the environmental conditions that make sufficient quantities of invertebrate prey available to support successful nesting by wading birds. This especially critical. Little work has been done to examine aspects of animal behavior, productivity, and pathways of energy flow through the system as related to hydropattern and disturbance. This is unfortunate because of the ecological roles of invertebrates in food webs.

7. What are the community-level interactions of invertebrates?

Some studies of the invertebrate community are difficult to carry out in the field, yet require more space than the confines of laboratory aquaria. Construction of an experimental mesocosm is planned in ENP to perform certain kinds of investigations.

▸ Conduct mesocosm studies on predator-prey, competitive, and indirect interactions.

▸ Conduct mesocosm studies on the role of nutrient inputs into the Everglades in causing shifts in marsh food webs through effects on the invertebrate community.

▸ Conduct mesocosm studies to test potential control methods for non-native species.

Fluctuations in Herpetofauna Communities

Background

Members of the aquatic herpetofauna are often very abundant components of ecosystems in these subregions. In particular, amphibians may be found over the widest range of habitats, from temporary pools formed in the wet season to the deepest, most permanent sloughs and strands. Salamanders, such as the peninsula newt, dwarf siren, and *Amphiuma*, are predators on small crustaceans, crayfish, and fishes. During their development, frogs and toads switch roles from being mainly herbivorous as tadpoles to becoming predators on insects, crustaceans, and other animals as adults. Aquatic snakes, while never as abundant as amphibians, are important predators on a variety of animals in the aquatic system. Several species of turtles are locally abundant in deeper, more permanent waters. All members of the aquatic herpetofauna are prey for larger Everglades predatory species; even alligators, when newly hatched, are taken as prey by large fishes and wading birds. Several species, especially the pig frog, alligator, and Florida softshell turtle, are harvested for food by humans. Those species and others collected for the pet trade provide some economic return in the ecosystem.

About a half dozen of the 25 established introduced species of reptiles and amphibians found in southern Florida are presently known to be established within the boundaries of Subregions 6 and 7. Several additional species have been collected here but probably have not established viable populations. Future colonizations by additional species are likely. During winter and dry seasons, massive mortality of the aquatic herpetofauna often occurs along area roadways as the animals move in search of water, warmth, or nesting sites.

The first scientific reports of the amphibians and reptiles of southern Florida were compositional and distributional descriptions published in the early decades of this century (summarized by Steiner and Loftus, in press). Carr (1940) provided a relatively complete record of the distribution of reptiles and amphibians in southern Florida, listing records for 162 species and subspecies for the entire State by county. His accounts presented general ecological data on habits, habitat, abundance, feeding, and reproduction. Carr (1940) documented nearly all of the presently known native species from southern Florida. The study by Duellman and Schwartz (1958) stands as the

most comprehensive work on herpetofauna of southern Florida. The monograph included detailed data on taxonomy, general ecology, and distribution for 85 species of reptiles and amphibians, including data from several collecting localities within ENP and the BC area. Dalrymple (1988) inventoried the herpetofauna of Long Pine Key, noting the presence of 52 species. Data on marsh herpetofauna have been collected during fish studies in the Park, but basic biological/ecological data on size frequency, food habits, and reproduction for the marsh herpetofauna have not been produced. An inventory for ENP is in press; some data are available for the Big Cypress Swamp (Duever et al. 1979). A monograph on the pig frog (*Rana grylio*), an ecologically and economically important amphibian, is applicable to the subregions, though based on data from the northern Everglades (Ligas 1960).

Most of the scientific information available for Everglades/BC herpetofauna has been collected in ENP, central Shark River Slough, or the Long Pine Key-Taylor Slough area. Much smaller data sets exist for the Rocky Glades area and the marsh-mangrove interface. There are few data for western Shark River Slough or the Big Cypress Swamp. Data on reproduction, food habits, age and growth, and other important life-history characteristics have been collected for only a few species, mainly from a small study area around Taylor Slough-Long Pine Key.

Critical questions and approaches

1. Throughout the subregions, what are the important details of herpetofauna community functioning and organization?

▸ Conduct a sampling program concentrated in short-hydroperiod, peripheral wetlands, where frogs and toads appear to be important aquatic species, and in long-hydroperiod marshes and strands. Continue sampling across several years to relate the data to seasonal and annual fluctuations in the environment of subregional habitats. These data collections would also monitor the status and habitat use of non-native species.

2. What are the details of important life-history parameters of key amphibian and reptile species?

Species should be studied at sites that represent a range of subregion environments. Little information on reproductive aspects, recruitment seasons, and growth has been collected. These data are needed to meet several objectives. The tasks below, in combination with data from Question 1, would provide the information needed to construct life tables for the species under different conditions in the system.

▸ Conduct a study of size frequencies and markers to estimate growth rates under different seasons and habitats.

▸ Conduct a study of fecundity and related parameters to estimate reproductive potential.

3. What are the key food-web relationships involving the herpetofauna of the Everglades/BC system?

Unraveling the connections and calculating flow networks will be valuable in addressing all the critical questions.

▸ Carry out direct observations of gut contents and feeding behaviors.

▸ Conduct stable isotope analysis of animal tissues to determine their primary carbon sources and energy pathways in different habitats. These data are also useful in predicting passage of biocontaminants through the system.

4. What are the biocontaminant loadings of representative members of the aquatic herpetofauna?

▸ Conduct periodic screening for contaminants to detect potential problems. Because many of these species are high-level predators in the aquatic systems, they can serve as early indicators of bioaccumulatory contaminants.

► Conduct studies of mercury mobilization, transfer, and direct effects on reptiles and amphibians. The mercury issue is a currently recognized problem with implications for the entire system.

5. What are the predator-prey and competitive interactions of the major herpetofauna species?

Some studies of community interactions and responses are difficult to carry out in the field, yet require more space than the confines of laboratory aquaria. An experimental mesocosm has been proposed to be built in ENP to perform certain kinds of investigations.

► Conduct mesocosm studies to provide data integral to construction of credible simulation models for the aquatic system. These would include studies on repercussions of the harvesting of herpetofauna on their predators and prey and on other biotic interaction hypotheses to clarify the roles of these species in the system.

Declines in Mammals Dependent on Freshwater Marsh Habitat

Background

Although no empirical data exist to document population trends of most species of mammals in the Everglades/BC basins that are not listed as endangered or threatened, it is widely speculated that several species dependent on freshwater marsh habitats have substantially declined due to water-management practices. Two species of principal concern are the round-tailed muskrat and the river otter. Other, more upland species such as the three native squirrels (gray, fox, and southern flying) and the black bear have become greatly reduced in numbers and range. In addition, the ecological consequences of an expanding population of introduced feral pigs have not been measured.

The mammals that have been most intensively studied in the Everglades/BC basins are the Florida panther (e.g., Belden 1988; McBride 1985; Smith and Bass 1994) and white-tailed deer (Boulay 1992; Miller 1993; Sargent 1992; Smith and Bass 1994; Zultowsky 1992). More limited, local studies and censuses have been conducted for the fox squirrel (Jodice 1993; Jodice and Humphrey 1991; Williams and Humphrey 1979), round-tailed muskrat (Tilmant 1975), Everglades mink (Smith 1980; Humphrey and Zinn 1982) and black bear (Brady and Maehr 1985).

With the exception of the well-studied panther and deer, there is only limited information on population trends, regional distribution patterns, or the biology or population ecology of most Everglades/BC mammals. The basic need is for development of census protocols for a number of these species, initiation of censuses based on these protocols, and a series of field ecology studies for species suspected of having declined and/or been adversely affected by management practices. Recently initiated efforts to design models for predicting population responses of panther and deer to management alternatives must receive a high priority (D. Fleming, pers. comm.).

Relative to spatial aspects, these mammals occur collectively throughout the Everglades/BC basins. The current uncertainties regarding the status of each, or the nature of limiting factors or adverse management impacts, argues that no geographical limitations be placed on initial censuses or studies.

Current scientific studies

Florida panther and white-tailed deer continue to be studied in the BC area, through projects coordinated by the FGFWFC and FWS for the panther and by Dr. Ron Labisky (UF) and the NPS for the deer. The Systematic Reconnaissance Flights at ENP include a dry-season and wet-season census of deer in Shark Slough. A very small study of food habits of feral pigs is being coordinated through ENP. Development of ATLSS models for panther and deer is continuing, under the direction of Dr. Lou Gross (UT) and Dr. Michael Huston (ORNL), respectively. No other mammal projects are currently active for these subregions.

Critical questions and approaches

1. What are the population trends of the marsh rabbit, round-tailed muskrat and river otter? What other species have declined in numbers or experienced reduction in ranges (squirrel species, etc.)?

- Conduct regular censuses in key areas for each species, repeated at least every 5 years.

2. What have been the impacts on natural communities of population increase and range expansion by feral pigs?

- Establish a comprehensive study of feral pig movements, behavior, and population levels in both subregions.

3. How are deer and panther interactions changing over the landscape?

- Continue development and evaluation of panther and deer models for the freshwater basins of the southern Everglades/BC.

Massive Declines in Wading Birds Throughout the Everglades/BC System

Background

The total number of wading birds nesting in these two subregions, for the five species that numerically dominated the traditional Everglades colonies (great egret, snowy egret, tricolored heron, white ibis, wood stork), appears to have declined by more than 95% from peak estimates of nesting birds in the 1930s. Peak annual estimates of nesting waders in these traditional colonies is estimated at 180,000-245,000 birds during the 1930s, compared to peak numbers of 5,700-7,500 nesting birds in the decade between 1984-1993 (Ogden 1994).

A good case has been made that wading birds are among the most important vertebrate indicators of ecological trends in the Everglades basin (Kushlan 1993; Ogden 1993). The current wading bird database for the southern Everglades contains considerable information on colony locations, numbers and species of nesting birds, timing and success of colonies, basic reproductive biology and food habits for the principal species, foraging patterns around colonies, regional foraging patterns of total wader populations (SRF data), and long-term population trends. These data have shown that most wading birds in the predrainage Everglades nested in the extreme southern portion of the basin, with the larger traditional colonies located either along the mangrove/freshwater marsh interface at the lower end of Shark Slough or within the belt of mangrove forest downstream from the Big Cypress and southern Everglades systems. A current hypothesis is that the combination of mainland estuaries and adjacent freshwater marshes in the far southern Everglades provided a relatively greater range of foraging habitat conditions and higher levels of primary/secondary production than did other regions in the Everglades basin (Bancroft et al. 1994; Frederick and Spalding 1994). Wading birds have responded to unnatural alterations in hydropatterns by: 1) reducing the number of birds attempting to nest, 2) relocating colonies, 3) changing the timing of nesting, and 4) having fewer years of successful nesting. Relocation of nesting has occurred primarily by birds moving away from traditional colony sites to the WCAs; the affected birds have for the most part been the smaller species of waders that have relatively short foraging ranges around a colony, and thus the pattern of colony relocations may be a response to changes in locations within the Everglades basin of the longer hydroperiod pools. Changes in timing of nesting, primarily by storks, appears to be a response to degradation of early dry-season foraging habitat in the mainland estuaries. Changes in location and timing of nesting may be the major causes for the great reductions in nesting effort and colony success rates among all species.

At this point, substantial improvement in understanding the relationships between decline in wading birds and changes in hydropatterns in the southern Everglades that have resulted from water management practices will require increased study of the: 1) dynamics of prey populations and 2) specific foraging strategies and patterns associated with successful nesting of wading birds. These birds feed primarily on small fishes and the larger aquatic invertebrates. Production and survival of these prey species in each of the major habitats/communities of the Everglades, as affected by water quantity and quality parameters, are currently being measured only for deep water,

marsh sloughs, and estuarine flats and creeks (Loftus and Eklund 1994; Lorenz 1993). The water management strategies that will recover these prey populations and the ecological processes that must be understood as a framework for designing these management strategies are yet to be determined.

Data on wading bird feeding patterns related to colony success patterns has been reported by Frohring (1988), and this topic is currently being investigated by Frederick (1993). P. Frederick and M. Spalding (pers. comm.) have initiated a study of great egret reproductive performance related to mercury levels in tissue and have developed a proposal for a study of the ecology and impacts of *Eustrongylides* (see below) on wading bird colony success rates. A series of interactive models designed to predict wood stork/wading bird responses to alternative management plans is currently being developed through a coordinated program between ENP, the Florida office of NBS, and UT (D. Fleming, pers. comm.). These models have the potential for being selected as a primary tool for evaluating alternative redesign proposals for the feasibility phase of the C&SF Restudy.

It has been proposed that the predrainage Everglades was able to sustain large numbers of wading birds because its large spatial extent, habitat heterogeneity, and dynamic hydrological patterns combined to create many optional foraging sites under a wide range of rainfall patterns. Thus the highly mobile waders could adjust the location and timing of nesting between years, in response to seasonal and annual differences in hydropatterns. Science and management questions raised by this issue require a broad-scale assessment, both in terms of geographical extent and, for a wide range of communities, dynamics of prey populations related to hydrological variables.

Current scientific studies

Wading bird nesting colonies continue to be minimally censused in Subregion 6, but not in Subregion 7. Total wading bird numbers are measured annually, primarily during six dry-season months and a single wet-season month, by SRFs. Dr. Peter Frederick is continuing a study of wading bird foraging behavior related to colony dynamics in the WCAs and in the Shark Slough of Subregion 6. Development of the ATLSS wading bird models is being coordinated by Dr. W.F. Wolf (ORNL and UT).

Critical questions and approaches

1. What are the key relationships between wading birds and their prey over the landscape?

Specific questions that should be answered include: Are mainland estuarine habitats potentially more productive of these prey species, and capable of creating higher concentrations, than freshwater habitats, and if so, how and by what processes?

▸ Determine the relationships between characteristics of small fish/aquatic macroinvertebrate populations and water quantity and quality patterns (including salinity) for major wading bird foraging habitats. Priority study sites should include most mainland estuarine habitats (tidal and nontidal creeks, brackish marshes, marl flats, etc.), along with shorter hydroperiod freshwater marl prairies and pond cypress/bald cypress mosaics.

2. What are the current spatial and temporal trends in wading bird colonies?

The wading bird colony record is the strongest vertebrate database from the Everglades basin, and its value for showing temporal and spatial responses to management practices is increasingly appreciated.

▸ Expand and standardize wading bird colony censuses to include all of Subregions 6 and 7. Currently aerial censuses of colonies do not cover the Big Cypress subregion, and the colony census protocol for ENP differs from that used in the WCAs and Lake Okeechobee. Regional response patterns by wading birds to hydrological conditions will not be fully known until a more comprehensive wading bird colony census is employed.

3. What can be learned about the regional pattern in nesting colonies from knowledge of landscape foraging patterns?

If clear linkages between regional hydropatterns, wading bird foraging patterns, and colony patterns can be shown, these relationships can have strong management applications during implementation and refinement of experimental programs for Everglades restoration.

▸ Examine the SRF database (1985-1994) to determine if regional foraging patterns of wading birds provide insights into the dynamics of colony patterns, specifically species composition, number of nesting birds, and location and timing of nesting.

4. What are the dimensions of the problem of the avian nematode parasite *Eustrongylides ignotus*?

Key questions pertain to possible relationships between this nematode and waters with high nutrient loads and to the potential for this nematode to cause high rates of mortality among nestling wading birds. In 1988, one ENP colony (Rodgers River Bay) had an 80% infestation rate among nestling herons and egrets.

▸ Determine the ecology of *Eustrongylides ignotus*.

5. Can a quantitative, predictive relationship between colony nesting success and hydrological conditions be developed?

▸ Continue on-the-ground studies of colony nesting success patterns, particularly to measure relationships between hydrological/climatological parameters and reproductive performance.

▸ Continue development of wading bird population models. Test model output against field data and revise models accordingly. Advance models to the stage at which credible scenario testing and simulations can be conducted.

▸ Continue development and refinement of regional, interactive wading bird models. Evaluate needs for an array of wading bird models to deal with the future restoration projects expected to occur at a range of spatial scales.

6. What is the extent of mercury and other toxin contamination of wading birds?

▸ Determine relationships between wading bird reproductive dynamics and contamination by mercury and other possible contaminants in the freshwater Everglades/BC.

Declines in Waterbirds (All Species Other Than Wading Birds)

Background

Long-term, qualitative observations suggest most of the formerly common waterbirds (e.g., pied-billed grebe, anhinga, coot, limpkin, mottled duck, wintering waterfowl in general) have substantially declined in numbers in the southern Everglades during the past several decades. Relatively little quantitative information exists for any of these species to either substantiate or refute the observations.

The common perception is that all species of waterbirds once commonly associated with freshwater Everglades communities have become numerically much less common and less widely distributed in the system. Although this perception is poorly documented, the very limited amount of quantitative data that do exist support the perception for a few species. A waterfowl and coot census in ENP in the winter of 1977-1978 revealed approximately 70,000 birds (about 50% coots) along a standardized census route (Kushlan et al. 1982). Similar annual censuses along the same route between 1991 and 1993 produced an annual mean of 530 birds (<20% coots; O. Bass, pers. comm.). Aerial censuses of West Lake, ENP, during the late 1960s revealed maximum wintering populations of 50,000 coots; fewer than 500 coots have wintered on the same lake since 1988 (J. Ogden, pers.

comm.). Almost certainly, across-the-board declines of a number of taxonomically and ecologically dissimilar waterbirds have occurred for a complex array of reasons, probably including: 1) outright loss of wetlands, 2) reductions in food availability in remaining wetlands caused by altered hydropatterns, 3) reductions in food caused by increases in salinity in mainland estuarine lakes, and 4) problems for migratory species occurring outside the Everglades. Population trends and baseline population measures need to be determined for these species by means of systematic reviews of historical data and implementation of censuses for select species and habitats.

Relative to spatial aspects, these species occur collectively throughout a broad range of freshwater and estuarine habitats. Perhaps characteristic of many wetland bird species, several of these species are known to make, or are suspected of making, sizable range shifts in response to seasonal and annual differences in hydropatterns. Their food habits are just as diverse and include submerged vegetation (coot, some ducks), aquatic insects (gallinules), apple snails (limpkin), and fishes (grebe, anhinga).

Current scientific studies

Except for a single, mid-winter census of waterfowl in Subregion 6 and on-going work on the endangered snail kite (see chapter on endangered species in this document), no studies of these species are currently active.

Critical questions and approaches

1. What are the spatial and temporal trends in populations of waterbirds not previously or regularly censused?

Censusing of additional waterbird species should become part of a much more comprehensive regional census program for the Everglades/BC basins, designed to measure species responses across a wide range of habitats and from the full spectrum of food habits guilds.

- Develop census protocols for grebe, anhinga, and limpkin.
- Review established census protocols for coot and waterfowl.

Decline in Numbers and Shift in Distribution of the American Alligator

Background

The American alligator is one of the most ecologically significant of the larger vertebrates in the Everglades and BC basins. As such, a properly designed monitoring program for this animal can serve both to define the nature of ecological problems in these systems and to measure progress towards achievement of restoration goals. Ecological studies of the alligator in ENP have shown that recent water-management strategies have caused reduced reproductive effort, increased frequencies of nest flooding, and increased rates of juvenile mortality (G. Dalrymple, pers. comm.; Fleming 1991; Kushlan and Jacobsen 1990). While these recent studies have produced valuable information on southern Everglades alligators, considerable additional data is required for improving alligator population models and for strengthening the utility of this species as an indicator of ecosystem conditions.

American alligators in the southern Everglades have shown large changes in numbers and distribution in response to the shifting influences of over-harvesting, protection, and habitat alterations (Craighead 1968; Mazzotti and Brandt 1994). Perhaps the most important ecological change has been the substantial population reduction in the higher elevation freshwater marshes flanking deeper sloughs and in the inner, more freshwater portions of the mainland mangrove regions. Craighead (1968) suggested alligators declined in these areas due to overdrainage in the former and increased salinities in the latter. Conversely, numbers have increased in the deeper central sloughs, in areas that apparently were too deeply flooded in the predrainage Everglades to support a large nesting population. The central Shark Slough now supports the highest densities of nesting alligators in ENP (Fleming 1991).

Fleming (1991) showed the number of adult female alligators that initiated nesting in Shark Slough was related to areal extent of surface water remaining in the study area at the end of each dry season. Thus, the

increased frequency of major drydown events in Shark Slough, as a consequence of recent water-management practices, has become the single most important factor responsible for reduced production by alligators in the primary habitat for this population (D. Fleming, pers. comm.).

Understanding the importance of the alligator as an indicator of ecosystem conditions requires that additional scientific investigation be conducted and one or more models of alligator population dynamics related to hydrological patterns be developed and evaluated. We know much less about alligator reproductive ecology, annual habitat patterns, and demography in cypress, mangrove, and marl soil communities than in Shark Slough communities. In all communities, empirical databases must be enlarged for all of these parameters but especially for relationships between reproductive performance, population structure and distribution, and hydrological/contaminant (mercury) parameters. An improved monitoring capability will require development of refined census protocols, most importantly for cypress and mangrove communities.

Relative to spatial aspects, scientific investigations of alligators in the Everglades/BC systems should be conducted in large study areas representative of major community types in these subregions. The Shark Slough study area (Fleming 1991) includes approximately 110,400 ha (272,798 acres) of prairie and slough marshes.

Current scientific studies

The program of SRFs to measure alligator nesting effort and success was expanded in 1994 to cover both Shark and Taylor sloughs in Subregion 6. Development of an ATLSS model for the alligator is being coordinated by Dr. W.F. Wolff (ORNL and UT). Surveys of alligator body condition and health, particularly relative to recent high waters are being conducted by Dr. G. Dalrymple in the Shark Valley area.

Critical questions and approaches

1. What are the continuing trends in alligator populations as related to hydrological conditions?

Current aerial monitoring of alligator nesting performance is limited to Shark Slough and adjacent higher elevation marshes (Fleming 1991) and should be expanded.

- Develop protocols and implement long-term monitoring for measuring alligator nesting patterns related to hydrological conditions. This should include cypress, mangrove, and marl soil communities.

2. What are the differences in population dynamics among wetland community types?

- Develop protocol and implement monitoring to measure seasonal and annual alligator population structure (age and sex classes) related to community types. Census techniques for measuring population structure of alligators in the canal along the Shark Valley observation tower road have been evaluated by G. Dalrymple (pers. comm.). Fleming (1991) recommended studies of: a) daily and seasonal activity patterns, movements, activity ranges, and habitat preferences by sex and age classes; b) seasonal food habits by sex and age classes; and c) sex- and age-specific growth and survival rates.

- Continue development, evaluation, and refinement of alligator population model(s).

Loss of Species from Upland Communities

Background

The continuing, possibly accelerating, loss of species from the upland communities of Subregions 6 and 7 and the Florida Keys is a major concern. Thinking and planning about Everglades restoration has focused, quite understandably, on the expansive wetlands. The fact that upland biotic communities are an integral part of the southern Everglades ecosystem has often been entirely overlooked or dismissed with token comment. Points that seem to be even less generally appreciated are: 1) The fragmented uplands at the southern extremities of the coastal ridges in Subregions 6 and 7 and the Florida Keys harbor most of the biological endemism that exists in South

Florida's terrestrial communities, as well as a large proportion of the entire Region's biotic diversity. 2) Within Subregions 6 and 7, economic development has eliminated 65-80% of the original upland habitats (pine forest, tropical/subtropical hardwood forest, short-hydroperiod prairie). 3) Reduced habitat area and deteriorated habitat quality have resulted in ongoing loss of plant and animal species, including endemics, from upland communities of Subregions 6 and 7. 4) Though issues of biodiversity are frequently discussed in relation to Everglades wetlands, all the known and imminently threatened losses of species in Subregions 6 and 7 appear to be associated with uplands. See Snyder et al. (1990) and Robertson and Frederick (1994) for recent reviews.

Disappearance from southern Florida uplands of bird species that had formerly nested there was noted as early as the 1950s. See references cited in Robertson (1955), Robertson and Kushlan (1974), and the two references above. Other losses are yet to be thoroughly compiled, but data are probably available at least for vascular plants and other terrestrial vertebrates from early biological collections. Historical data on lower plants and invertebrates are poor. Upland disturbance and development in southern Florida occurred late enough that much of it was well documented by aerial photography, in particular photos taken regularly by counties and municipalities for tax purposes. This information source still needs to be systematically investigated. Possible indirect human effects, as by alteration of fire regimes, will require examination of appropriate databases. Robertson and Frederick (1994) offered a tentative review of some of the philosophical and practical problems likely to beset upland restoration efforts in southern Florida.

Current scientific studies

Surveys of upland bird communities of Long Pine Key are being conducted by Drs. W.R. Robertson, Jr., and K. Meyer. Results are being interpreted in relation to hurricane damage and potential for restoration. The work is funded by the Hurricane Andrew research program. Similar work by D. Jansen is focused on red-cockaded woodpeckers. Breeding colonies are under intensive observation over several or more years. Both projects are noted in Table 6.

Critical questions and approaches

1. What is the extent of biodiversity loss in uplands, how has the trend changed recently, and can the trend be arrested or even reversed?

Understanding the factors causing widespread loss of biodiversity from upland communities in these subregions is crucial to determining if feasible corrective measures exist. A comprehensive study of population dynamics, habitat requirements, and factors controlling population size is urgently needed for several vertebrate species known to be at risk of extirpation. The study would look intensively at past and present biotas and land-use history of upland communities. Travel to major museums in the eastern and central U.S. where biological collections from relevant areas are held would probably be necessary. As the project develops, it may be advisable to examine specific aspects of upland communities farther north in the Everglades system or comparable habitats south of Florida (northern Bahamas, Cuba). The principal tasks would be:

- Characterize the temporal and spatial patterns of all documentable loss or decline of species in uplands of Subregions 6 and 7, southeastern mainland Florida, and the Florida Keys.

- Determine in detail how these patterns relate to direct and indirect effects of upland development and to possible nonanthropogenic forces.

- Investigate the feasibility of available means to correct, mitigate, or restore biotic losses in upland communities. The possibility of reintroductions, habitat modifications, improvement (or establishment) of landscape connectivity, and other innovative approaches should be investigated by interdisciplinary scientific teams.

Surface Water Quality Entering and Leaving Native American Lands

Background

The Seminole and Miccosukee Indian Tribes are Federally recognized tribes. The Federal Government is trustee of their lands and resources and protector of their rights. Indian lands of the Miccosukee and Seminole Tribes are subjected to flows of surface water originating from upstream that are contaminated with high levels of nitrogen, phosphorus, heavy metals, and other pollutants. These pollutants are generally attributed to intensive upstream agricultural development and other anthropogenic activities. Of special concern are heavy metals (methylated mercury) in surface waters and sediments.

This pollution has, over the years, resulted in contaminated fish and wildlife, which tribal members consume as part of their traditional subsistence hunting and fishing lifestyle. Tribal lands are being used as filters and treatment areas for polluted waters. This has resulted in conversion of wetlands to areas lacking the natural plant and animal diversity of the past. The tribes must be provided resources necessary for full participation in scientific data collection needed for planning and implementation of the restoration effort, for tribal rights protection, and for assurance of the Federal Government's responsibility to protect tribal trust resources. Scientific information needs of both the Miccosukee Tribe and the Seminole Tribe are related to needs of the Everglades Restoration and the Federal Government's responsibility to protect trust resources and tribal rights. The needs of both tribes are similar, and those following apply to both tribes.

Critical questions and approaches

1. What is the quality of water entering and leaving the reservations in relation to established Federal, State, and tribal standards?

- Develop automated water quality monitoring stations to monitor the entrance and exit sources of surface waters in the Big Cypress Seminole and Miccosukee Reservations; 11 sampling stations (7 on Big Cypress Seminole, 4 on Miccosukee) are required along with frequent and event-initiated sample analysis to establish baseline data and event-related data.

2. What quantities of water are entering and leaving the reservations?

- Develop water quantity flow measurement stations at each water quality monitoring station.

3. What are the site-specific atmospheric conditions influencing water quality and quantity entering and leaving the reservations? What is the air quality on the reservations as it relates to deposition of pollutants?

- Install eight full-time meteorological monitoring stations (five on Big Cypress, three on Miccosukee) to monitor atmospheric conditions and provide data for event data correlation.

- Provide monitoring of air and rain quality at two sites on each reservation utilizing wet/dry deposition boxes and PM10 high-volume monitors.

- Develop a quality assurance/quality control plan for the water quality sampling process, data management, and analysis. All data and samples from the sites will be sent to laboratories for required chemical analyses. Numerical data will be stored in a tribal database that will be available for the overall restoration effort. The majority of physical parameters will be monitored by daily retrieval of data through radiotelemetry.

BIBLIOGRAPHY

Alexander, T.R., and A.G. Crook. 1984. Recent vegetational changes in South Florida. Pages 199-210 *in* P.J. Gleason, editor. Environments of South Florida: Present and Past II. Miami Geological Society, Coral Gables, Florida.

Armentano, T.V., R.F. Doren, W.J. Platt, and T.J. Mullins. 1995. Effects of Hurricane Andrew on coastal and interior forests of southern Florida: overview and synthesis. Journal of Coastal Research 21:111-144.

Avery, G.N., and L.L. Loope. 1980. Endemic taxa in the flora of South Florida. Report T-558. SFRC, ENP, Homestead, Florida.

Bancroft, G.T., S.D. Jewell, and A.M. Strong. 1990. Foraging and nesting ecology of herons in the lower Everglades relative to water conditions. Final report. NAS, Tavernier, Florida.

Bancroft, G.T., J.C. Ogden, and B.W. Patty. 1988. Wading bird colony formation and turnover relative to rainfall in the Corkscrew Swamp area of Florida during 1982 through 1985. Wilson Bulletin 100:50-59.

Bancroft, G.T., A.M. Strong, R.J. Sawicki, W. Hoffman, and S.D. Jewell. 1994. Relationships among wading bird foraging patterns, colony locations, and hydrology in the Everglades. Pages 615-658 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Belden, R.C. 1988. The Florida panther. Pages 514-532 *in* W.J. Chandler, editor. Audubon Wildlife Report, 1988/1989. NAS, New York.

Boulay, M.C. 1992. Mortality and recruitment of white-tailed deer fawns in the wet prairie/tree island habitat of the Everglades. Master's thesis. UF, Gainesville, Florida.

Brady, J.R., and D.S. Maehr. 1985. Distribution of black bears in Florida. Florida Field Naturalist 13:1-7.

Browder, J.A., S. Black, P. Schroeder, M. Brown, M. Newman, D. Cottrell, D. Black, R. Pope, and P. Pope. 1981. Perspective on the ecological causes and effects of the variable algal composition of southern Everglades periphyton. SFRC, ENP, Homestead, Florida.

Browder, J.A., P.J. Gleason, and D.R. Swift. 1994. Periphyton in the Everglades: spatial variation, environmental correlates, and ecological implications. Pages 379-418 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Carlson, J.E., and M.J. Duever. 1977. Seasonal fish population fluctuations in a South Florida swamp. Proceedings of the Southeastern Association of Fish and Wildlife Agencies 31:603-611.

Carr, A.F. Jr. 1940. A contribution to the herpetology of Florida. University of Florida Publications, Biological Science Series 3(1):1-118.

Carter, M.R., L.A. Burns, T.E. Cavender, K.R. Dugger, P.L. Fore, D.B. Hicks, H.L. Revells, and T.W. Schmidt. 1973. Ecosystems analysis of the Big Cypress Swamp and estuaries. EPA 904/9-74-002. EPA Region IV, Atlanta, Georgia.

Central and Southern Florida Flood Control District. 1950. A report on water resources of Everglades National Park Florida. C&SF FCD, West Palm Beach, Florida.

Craighead, F.C. 1968. The role of the alligator in shaping plant communities and maintaining wildlife in the southern Everglades. Florida Naturalist 41:2-7, 69-74, 94.

Craighead, F.C. 1971. The Trees of South Florida. Volume I, The Natural Environments and Their Succession. University of Miami Press, Coral Gables, Florida.

Dalrymple, G.H. 1988. The herpetofauna of Long Pine Key, Everglades National Park, in relation to vegetation and hydrology. Pages 72-86 *in* R.C. Szaro, K.E. Stevenson, and D.R. Patton, editors. The Management of Amphibians, Reptiles, and Small Mammals in North America. USDA, U.S. Forest Service Symposium, Gen. Tech. Rept. RM-166, Flagstaff, Arizona.

Davis, J. H. 1943. The natural features of southern Florida, especially the vegetation, and the Everglades. Florida Geological Survey Geological Bulletin No. 25.

Doren, R.F., T.V. Armentano, L. Whiteaker, and R.D. Jones. 1995. Marsh vegetation patterns and phosphorous gradients in the Everglades ecosystem. South Florida Natural Resources Center Report, ENP, Homestead, Florida.

Doren, R.F., L.D. Whiteaker, and A.M. LaRosa. 1991. Evaluation of fire as a management tool for controlling *Schinus terebinthifolius* as secondary successional growth on abandoned agricultural land. Environmental Management 15:121-129.

Duellman, W.E., and A. Schwartz. 1958. Amphibians and reptiles of southern Florida. Bulletin Florida State Museum 3:181-324.

Duever, M.J. 1984. Environmental factors controlling plant communities of the Big Cypress Swamp. Pages 127-137 *in* P.J. Gleason, editor. Environments of South Florida: Present and Past II. Miami Geological Society, Coral Gables, Florida.

Duever, M.J., J.E. Carlson, J.F. Meeder, L.C. Duever, L.H. Gunderson, L.A. Riopelle, T.R. Alexander, R.F. Myers, and D.P. Spangler. 1979. Resource inventory and analysis of the Big Cypress National Preserve. Final report to DOI, NPS. Center for Wetlands, UF, Gainesville, and NAS, Naples, Florida.

Ewel, J.J. 1986. Invasibility: lessons from South Florida. Pages 214-230 *in* H.A. Mooney, and J.A. Drake, editors. Ecology of Biological Invasions of North America and Hawaii. Springer-Verlag, Inc., New York.

Ewel, J.J., D.S. Ojima, D.A. Karl, and W.F. DeBusk. 1982. *Schinus* in successional ecosystems of Everglades National Park. Report T-676. SFRC, ENP, Homestead, Florida.

Fleming, D.M. 1991. Wildlife ecology studies. 1991 annual report, Vol. 1, Sect. V. SFRC, ENP, Homestead, Florida.

Franz, R. 1977. Observations on the food, feeding behavior, and parasites of the striped swamp snake, *Regina alleni*. Herpetologica 33:91-94.

Frederick, P.C. 1993. Wading bird nesting success studies in the Water Conservation Areas of the Everglades, 1992 and 1993. Final report to SFWMD, West Palm Beach, Florida.

Frederick, P.C., and M.W. Collopy. 1988. Reproductive ecology of wading birds in relation to water conditions in the Florida Everglades. FWS Cooperative Research Unit, UF, Gainesville, Florida.

Frederick, P.C., and W.F. Loftus. 1993. Responses of marsh fishes and breeding wading birds to low temperatures: a possible behavioral link between predator and prey. Estuaries 16(2):216-222.

Frederick, P.C., and M.G. Spalding. 1994. Factors affecting reproductive success of wading birds. Pages 659-692 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Frohring, P.C. 1988. Herons in Everglades National Park. Report to NPS, ENP, Homestead, Florida.

Gunderson, L.H. 1989. Historical hydropatterns in wetland communities of Everglades National Park. Pages 1099-1111 *in* R.R. Sharitz and J.W. Gibbons, editors. Freshwater Wetlands and Wildlife, CONF-8603101. DOE Symposium Series No. 61. U.S. Department of Energy, Office of Scientific and Technical Information, Oak Ridge, Tennessee.

Gunderson, L.H. 1994. Vegetation of the Everglades: determinants of community composition. Pages 323-340 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Gunderson, L.H., and W.F. Loftus. 1993. The Everglades. Pages 199-255 *in* W.H. Martin, S.G. Boyce, and E.G. Echternacht, editors. Biodiversity of the Southeastern United States: Lowland Terrestrial Communities. John Wiley & Sons, New York.

Gunderson, L.H., and L.L. Loope. 1982a. An inventory of the plant communities in the Levee 28 Tieback area, Big Cypress National Preserve. Report T-664. SFRC, ENP, Homestead, Florida.

Gunderson, L.H., and L.L. Loope. 1982b. An inventory of the plant communities within the Deep Lake Strand Area, Big Cypress National Preserve. Report T-666. SFRC, ENP, Homestead, Florida.

Herndon, A., and D. Taylor. 1986. Response of a *Muhlenbergia* prairie to repeated burning: changes in above-ground biomass. Report SFRC-86/05. SFRC, ENP, Homestead, Florida.

Hofstetter, R. H. 1984. The effect of fire on the pineland and sawgrass communities of southern Florida. Pages 465-476 *in* P.J. Gleason, editor. Environments of South Florida: Present and Past II. Miami Geological Society, Coral Gables, Florida.

Humphrey, S.R., and T.L. Zinn. 1982. Seasonal habitat use by river otters and Everglades mink in Florida. Journal of Wildlife Management 46:375-381.

Hunt, B. P. 1952. Food relationships between Florida spotted gar and other organisms in the Tamiami Canal, Dade County, Florida. Transactions of the American Fisheries Society 82:13-33.

Jacobsen, T., and J.A. Kushlan. 1989. Growth dynamics in the American alligator (*Alligator mississippiensis*). Journal of the Zoological Society London 219:309-328.

Jodice, P.G.R. 1993. Movement patterns of translocated Big Cypress fox squirrels (*Sciurus niger avicennia*). Florida Scientist 56:1-6.

Jodice, P.G.R., and S.R. Humphrey. 1991. Ecology and translocation of urban populations of Big Cypress fox squirrels (*Sciurus niger avicennia*). Final report. UF, Gainesville, Florida.

Johnson, L. 1958. A survey of the water resources of Everglades National Park, Florida. Lamar Johnson, Consulting Engineer, Lake Worth, Florida.

Klein, H., W.J. Schneider, B.F. McPherson, and T.J. Buchanan. 1970. Some hydrologic and biologic aspects of the Big Cypress Swamp drainage area, Southern Florida. USGS, Tallahassee, Florida.

Kolipinski, M.C., and A. L. Higer. 1969. Some aspects of the effects of the quantity and quality of water on biological communities in Everglades National Park. Open File Report 69007. USGS, Tallahassee, Florida.

Kushlan, J.A. 1974. Effects of a natural fish kill on the water quality, plankton, and fish population of a pond in the Big Cypress Swamp, Florida. Transactions of the American Fisheries Society 103:235-243.

Kushlan, J.A. 1975. Population changes of the apple snail (*Pomacea paludosa*) in the southern Everglades. Nautilus 89:21-23.

Kushlan, J.A. 1980. Population fluctuations of Everglades fishes. Copeia 1980:870-874.

Kushlan, J.A. 1986. Responses of wading birds to seasonally fluctuating water levels: strategies and their limits. Colonial Waterbirds 9:155-162.

Kushlan, J.A. 1993. Waterbirds as bioindicators of wetland change: are they a valuable tool? Pages 48-55 *in* M. Moser, R.C. Prentice, and J. van Vessem, editors. Waterfowl and Wetland Conservation in the 1990s - a Global Perspective. Proceedings IWRB Symposium, St. Petersburg Beach, Florida. IWRB Spec. Publ. No. 26, Slimbridge, U.K.

Kushlan, J.A., O.L. Bass Jr., and L.C. McEwan. 1982. Wintering waterfowl in Everglades National Park. Report T-670. ENP, Homestead, Florida.

Kushlan, J.A., and T. Jacobsen. 1990. Environmental variability and reproductive success of Everglades alligators. Journal of Herpetology 24:176-184.

Kushlan, J.A., and M.S. Kushlan. 1979. Observations on crayfish in the Everglades, Florida, U.S.A. Crustaceana Supplement 5:116-120.

Kushlan, J.A., and M.S. Kushlan. 1980a. Everglades alligator nests: nesting site for marsh reptiles. Copeia 1980:930-932.

Kushlan, J.A., and M.S. Kushlan. 1980b. Population fluctuations of the prawn, *Palaemonetes paludosus*, in the Everglades. American Midland Naturalist 103:401-403.

Kushlan, J.A:, J.C. Ogden, and A.L. Higer. 1975. Relation of water level and fish availability to Wood Stork reproduction in the southern Everglades, Florida. Report 75-434. USGS, Tallahassee, Florida.

Ligas, F.J. 1960. The Everglades bullfrog: life history and management. Report of the FGFWFC, Federal Aid Project W-39-R. Tallahassee, Florida.

Loftus, W.F. 1988. Distribution and ecology of exotic fishes in Everglades National Park. Pages 24-34 *in* L.K. Thomas, editor. Management of Exotic Species in Natural Communities. Volume 5, Proceedings of the 1986 Conference on Science in the National Parks, Fort Collins, Colorado.

Loftus, W.F., and O.L. Bass Jr. 1992. Mercury threatens wildlife resources and human health in Everglades NP. Park Science 12:18-20.

Loftus, W.F., J.D. Chapman, and R. Conrow. 1990. Hydroperiod effects on Everglades marsh food webs, with relation to marsh restoration efforts. Pages 1-22 *in* G. Larson and M. Soukup, editors. Fisheries and Coastal Wetlands Research. Volume 6, Proceedings of the 1986 Conference on Science in National Parks.

Loftus, W.F. and A.-M. Eklund. 1994. Long-term dynamics of an Everglades fish community. Pages 461-483 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The System and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Loftus, W.F. and J.A. Kushlan. 1987. Freshwater fishes of southern Florida. Bulletin of the Florida State Museum, Biological Sciences 31:147-344.

Loope, L., M. Duever, A. Herndon, J. Snyder, and D. Jansen. 1994. Hurricane impact on uplands and freshwater swamp forest. BioScience 44(4):238-246.

Loope, L.L., and V.L. Dunevitz. 1981. Investigations of early plant succession on abandoned farmland in Everglades National Park. Report T-644. SFRC, ENP, Homestead, Florida.

Lorenz, J.J. 1993. Influence of hydrology on fish populations in the mangrove dominated zones of the C-111 and Taylor Slough basins and Biscayne Bay. Progress report. NAS, Tavernier, Florida.

Maehr, D.S., R.C. Belden, E.D. Land, and L. Wilkins. 1989. Food habits of panthers in southwest Florida. Journal of Wildlife Management 54(3):420-423.

Mazzotti, F.J., and L.A. Brandt. 1994. Ecology of the American alligator in a seasonally fluctuating environment. Pages 485-505 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

McBride, R. 1985. Population status of the Florida panther in the Everglades National Park and Big Cypress National Preserve. Final report. ENP.

McCown, J.W. 1991. Big Cypress deer/panther relationships: deer herd health and reproduction. Bureau of Wildlife Research, FGFWFC, Tallahassee, Florida.

McPherson, B.F. 1973. Vegetation map of southern parts of Subareas A and C, Big Cypress Swamp, Florida. Hydrologic Investigations Atlas HA-492. USGS.

Miller, K.E. 1993. Habitat use by white-tailed deer in the Everglades: tree islands in a seasonally flooded landscape. Master's thesis. UF, Gainesville, Florida.

Myers, R.L. 1983. Site susceptibility to invasion by the exotic tree *Melaleuca quinquenervia* in southern Florida. Journal of Applied Ecology 20:645-658.

Ogden, J.C. 1993. The Everglades story - the role of waterbirds in integrated management. Pages 240-244 *in* M. Moser, R.C. Prentice, and J. van Vessem, editors. Waterfowl and Wetland Conservation in the 1990s - a Global Perspective. Proceedings IWRB Symposium, St. Petersburg Beach, Florida. IWRB Special Publication No. 26, Slimbridge, U.K.

Ogden, J.C. 1994. A comparison of wading bird nesting colony dynamics (1931-1946 and 1974-1989) as an indication of ecosystem conditions in the southern Everglades. Pages 533-570 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Ogden, J.C., J.A. Kushlan, and J.A. Tilmant. 1978. The food habits and nesting success of wood storks in the Everglades National Park in 1974. Natural Resources Report No. 16. NPS, Washington, D.C.

Ogden, J.C., W.B. Robertson, G.E. Davis, and T.W. Schmidt. 1974 (revised). Pesticides, polychlorinated biphenyls and heavy metals in upper food chain levels, Everglades National Park and vicinity. South Florida Environmental Project: Report D1-SFEP-74-16. ENP, Homestead, Florida.

Olmsted, I., H. Dunevitz, and W.J. Platt. 1993. Effects of freezes on tropical trees in Everglades National Park Florida, USA. Tropical Ecology 34(1):17-34.

Olmsted, I., and L.L. Loope. 1984. Plant communities of Everglades National Park. SFRC, ENP, Homestead, Florida.

Olmsted, I.C., L.L. Loope, and R.E. Rintz. 1980. A survey and baseline analysis of aspects of the vegetation of Taylor Slough, Everglades National Park. Report T-586. SFRC, ENP, Homestead, Florida.

Olmsted, I., W.B. Robertson, J. Johnson, and O.L. Bass. 1983. The vegetation of Long Pine Key, Everglades National Park. Report SFRC-83/05. SFRC, ENP, Homestead, Florida.

Parker, G.G., G.E. Ferguson, S.K. Love. 1955. Water resources of southeastern Florida with special reference to the geology and ground water of the Miami area. Geological Survey Water-Supply Paper 1255. GPO, Washington, D.C.

Pimm, S.L., G.E. Davis, L. Loope, C.T. Roman, T.J. Smith III, and J.T. Tilmant. 1994. Hurricane Andrew. BioScience 44(4):224-229.

Raschke, R.L. 1993. Diatom (Bacillariophyta) community response to phosphorous in the Everglades National Park, USA. Phycologia 32(1):48-58.

Reark, J.B. 1961. Ecological investigations in the Everglades. Second annual report to Everglades National Park. UM, Coral Gables, Florida.

Reid, J.W. 1992. Copepoda (Crustacea) from fresh waters of the Florida Everglades, U.S.A., with a description of *Eucyclops conrowae* n. sp. Transactions of the American Microscopical Society 111:229-254.

Robertson, W.B. Jr. 1955. An analysis of breeding-bird populations in tropical Florida in relation to the vegetation. Ph.D. dissertation, University of Illinois, Urbana, Illinois.

Robertson, W.B. Jr., and P.C. Frederick. 1994. The faunal chapters: contexts, synthesis, and departures. Pages 709-737 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Robertson, W.B. Jr., and J.A. Kushlan. 1974. The southern Florida avifauna. Pages 414-452 *in* P.J. Gleason, editor. Environments of South Florida: Present and Past II. Miami Geological Society, Coral Gables, Florida.

Roman, C.T., N.G. Aumen, J.C. Trexler, R.J. Fennema, W.F. Loftus, and M.A. Soukup. 1994. Hurricane Andrew's impact on freshwater resources. BioScience 44(4):247-255.

Sargent, R.A. 1992. Movement ecology of adult male white-tailed deer in hunted and non-hunted populations in the wet prairie of the Everglades. Master's thesis. UF, Gainesville, Florida.

Scheidt, D.J. 1989. Pesticides and Everglades National Park: South Florida use and threat. Pages 365-375 *in* D.W. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Scheidt, D.J., M.D. Flora, and D.R. Walker. 1989. Water quality management for Everglades National Park. Pages 377-390 *in* D.W. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Smith, A.T. 1980. An environmental study of Everglades mink (*Mustela vison*). Report T-555. SFRC, ENP, Homestead, Florida.

Smith, J.T. III, M.B. Robblee, H.R. Wanless, and T.W. Doyle. 1994. Mangroves, hurricanes, and lightning strikes. BioScience 44(4):256-262.

Smith, T.R., and O.L. Bass Jr. 1994. Landscape, white-tailed deer, and the distribution of Florida panther in the Everglades. Pages 693-708 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Snyder, J.R. 1986. The impact of wet season and dry season prescribed fires on Miami Rock Ridge pineland, Everglades National Park. Report SFRC-86/06. SFRC, ENP, Homestead, Florida.

Snyder, J.R., A. Herndon, and W.B. Robertson Jr. 1990. South Florida rockland. Pages 230-277 *in* R.L. Myers and J.J. Ewel, editors. Ecosystems of Florida. University of Central Florida Press, Orlando, Florida.

Spier, L.P. 1991. Effects of season of burning on the population biology of *Jacquemontia curtisii*, a South Florida pineland endemic. Master's thesis. FIU, Miami, Florida.

Steiner, T.M. and W.F. Loftus. In press. An annotated inventory of the herpetofauna of Everglades National Park. Technical Report. NPS Southeast Region, Atlanta, Georgia.

Tilmant, J.T. 1975. Habitat utilization by round-tailed muskrats (*Neofiber alleni*) in Everglades National Park. Master's thesis. Humboldt State University, Arcata, California.

Tilmant, J.T., R.W. Curry, R. Jones, A. Szmant, J.C. Zieman, M. Flora, M.B. Robblee, D. Smith, R.W. Snow, and H. Wanless. 1994. Hurricane Andrew's effects on marine resources. BioScience 44(4):230-237.

Van Lent, T., and R. Johnson. 1993. Towards the restoration of Taylor Slough. ENP, Homestead, Florida.

Van Lent, T.J., and R.J. Johnson. Submitted. Water management for Taylor Slough, Everglades National Park, Florida. ASCE Journal of Water Resource Planning and Management.

Van Lent, T.J., R. Johnson, and R. Fennema. 1993. Water management in Taylor Slough and effects on Florida Bay. SFRC, ENP, Homestead, Florida.

Wade, D., J. Ewel, and R. Hofstetter. 1980. Fire in South Florida ecosystems. U.S. Forest Service General Technical Report No. SE-17. Southeast Forest Experiment Station, Asheville, North Carolina.

Walker, W.W. 1991. Water quality trends at inflows to Everglades National Park. Water Resources Bulletin 27(1):59-72.

Whiteaker, L.D., and R.F. Doren. 1989. Exotic plant species management strategies and list of exotic species in prioritized categories for Everglades National Park. DOI, NPS Southeast Regional Office, Atlanta, GA.

Wiemeyer, S.N., C.M. Bunck, and A.J. Krynitsky. 1988. Organochlorine pesticides, polychlorinated biphenyls, and mercury in osprey eggs--1970-79--and their relationships to shell thinning and productivity. Archives of Environmental Contamination and Toxicology 17:767-787.

Williams, K.S., and S.R. Humphrey. 1979. Distribution and status of the endangered Big Cypress fox squirrel (*Sciurus niger avicennia)* in Florida. Florida Scientist 42:201-205.

Zultowsky, J.M. 1992. Behavioral and spatial ecology of female white-tailed deer in the Everglades. Master's thesis. UF, Gainesville, Florida.

NATIVE AMERICAN BIBLIOGRAPHY

Agriculture Management Services Company, Inc. 1989. Project quality assurance plan for Seminole water resources management.

Carr, R.S., and J.C. Beriault. 1984. Prehistoric man in southern Florida. *In* P.J. Gleason, editor. Environments of South Florida: Present and Past II. Memoir II, Miami Geological Society, Miami, Florida.

Dames and Moore. 1994. Final environmental impact statement -- Miccosukee 3-1 exploratory well, Miccosukee Indian Reservation.

Lodge, T.E. 1994. The Everglades Handbook. St. Lucie Press, Delray Beach, Florida.

Miccosukee Tribe of Florida. 1993. Conceptual Land Use Plan.

Milleson, G.M. 1989. Hydrogeologic study of the Miccosukee Indian Reservation in Broward County, Florida.

Milleson, G.M. 1989. Southeast Hendry County groundwater model.

Paige, J.C., and L.F. Vanhorn. 1982. An ethnohistory of Big Cypress National Preserve, Florida.

Patterson, G.A. 1984. Miccosukee Wildlife Management Handbook.

Seminole Tribe of Florida. 1990. Big Cypress Reservation water management study.

Seminole Tribe of Florida and South Florida Water Management District. 1987. Water Rights Compact among the Seminole Tribe of Florida, the State of Florida, and the South Florida Water Management District.

U.S. Army Corps of Engineers. 1990. Report of pumping facilities at the Brighton Seminole Indian Reservation. COE, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1987. Technical report on surface water management analysis - Brighton Seminole Indian Reservation. COE, Jacksonville, Florida.

U.S. Soil Conservation Service. 1993. Soil survey - Big Cypress Indian Reservation.

U.S. Soil Conservation Service. 1986. Soil survey - Brighton Seminole Indian Reservation.

U.S. Soil Conservation Service. 1987. Soil survey - Miccosukee Indian Alligator Alley Reservation.

SUBREGION 8:

SOUTHERN COASTAL AREAS

INTRODUCTION

Subregion 8 includes the Atlantic Coast estuaries from South Biscayne Bay to Barnes Sound, Florida Bay proper and its fringing mangrove habitat, the Florida Keys and associated coral reef tract, and the West Coast estuaries from Whitewater Bay to Rookery Bay with their extensive mangrove habitats (Figure 1). This subregion includes a diversity of marine, estuarine, fringing, and terrestrial habitats. It is characterized by shallow water of naturally fluctuating salinities with extensive seagrass, mangrove, and coral reef habitats that are important nursery areas for many species, as well as critical habitat for other life stages.

The Florida Keys are a limestone island archipelago extending southwest over 320 km (199 mi) from the southern tip of the Florida mainland to the Dry Tortugas, 101 km (63 mi) west of Key West. They are bounded on the north and west by Biscayne Bay, Barnes and Blackwater sounds, Florida Bay, and the Gulf of Mexico. The Florida Keys National Marine Sanctuary includes 9500 km^2 (3668 mi^2) of submerged lands and waters between the southern tip of Key Biscayne and the Dry Tortugas Bank. North of Key Largo it includes Barnes and Card sounds. To the east and south, the oceanic boundary is the 300-m isobath. The FKNMS includes part of Florida Bay and the entire Florida reef tract, the largest barrier reef system on the Continental Shelf. The coral reef tract is characterized by a rich biodiversity that requires clear, naturally oligotrophic ocean water. The Florida Keys also include hardwood hammocks, coastal strand communities, and fringing mangrove, beach or rocky habitat.

BACKGROUND

The restoration objectives for South Florida (as presented in SSG 1993) are largely dependent upon restoration of natural freshwater delivery and quality to the subregion. The focus of restored freshwater inflow includes redirecting flow into Biscayne Bay, Card Sound, and Barnes Sound via the C-111 system and restoring flow into northern Florida Bay via Taylor Slough and Shark Slough. A review of existing management and science plans was completed to determine the extent of area within the subregion covered under existing plans with emphasis on restoring freshwater inflows into the estuaries of Subregion 8. In addition, upland impacts, particularly related to continued development of the Florida Keys, were evaluated relative to inclusion in existing plans. Critical gaps in areas or information, considered essential for management decisions supporting restoration of the subregion as a whole, were identified and are highlighted in Figure 16, along with objectives for Subregion 8. These gaps resulted in the science recommendations included in this chapter.

A bibliography for Subregion 8 is attached. Several comprehensive publications are of special note. These include proceedings of seven conferences: 1995 Florida Bay Science Conference (Brock et al. 1995); Second Coastal Wetland Ecology and Management Symposium (Meeder and Turner 1994); 1992 Symposium on the Florida Keys Regional Ecosystem, published as *Bulletin of Marine Science* 54(3); 1987 Symposium on Florida Bay, A Subtropical Lagoon, published as *Bulletin of Marine Science* 44(1); 1991 Research Planning Workshop for the FKNMS (Harwell 1991); Florida Coastal Ocean Sciences Symposium (Mooers 1994); and Virginia Key Coastal Ocean Sciences Symposium (Mooers 1992). These proceedings, which together contain 68 papers and more than 200 abstracts on Florida Bay and the Florida Keys, are referenced as single publications; papers and abstracts are not listed individually. Schmidt (1991) contains 520 citations on the coastal and estuarine areas of ENP. Pikula and Elswick (1992) includes 552 citations on the Florida Keys. Hale (1993) is a bibliography of more than 1700 references on Biscayne Bay. Cantillo et al. (1995) present a compilation of scientific work on Florida Bay along with an extensive annotated bibliography.

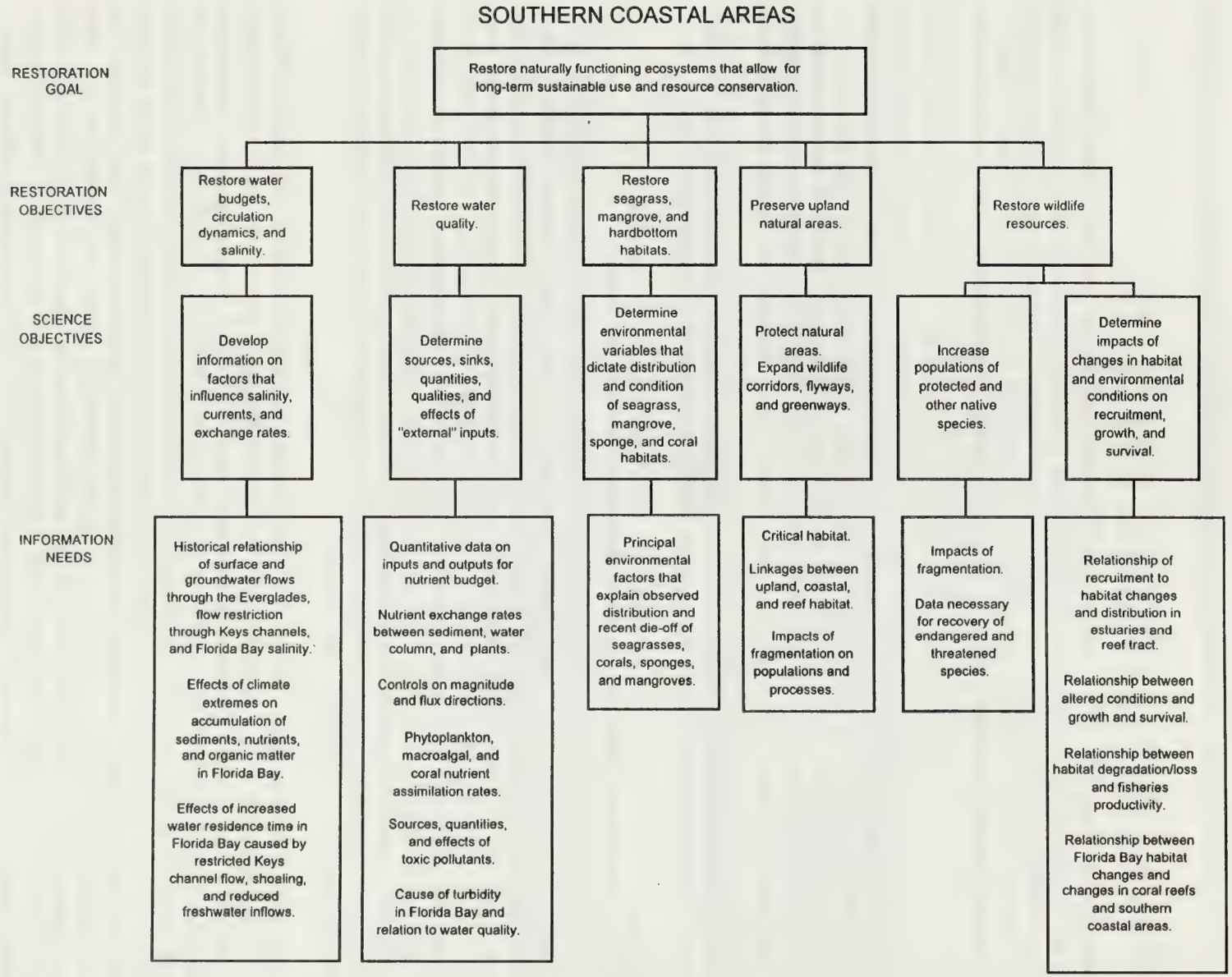

SOUTHERN COASTAL AREAS
RESTORATION GOAL
Restore naturally functioning ecosystems that allow for long-term sustainable use and resource conservation.
RESTORATION OBJECTIVES
Restore water budgets, circulation dynamics, and salinity.
Restore water quality.
Restore seagrass, mangrove, and hardbottom habitats.
Preserve upland natural areas.
Restore wildlife resources.
SCIENCE OBJECTIVES
Develop information on factors that influence salinity, currents, and exchange rates.
Determine sources, sinks, quantities, qualities, and effects of "external" inputs.
Determine environmental variables that dictate distribution and condition of seagrass, mangrove, sponge, and coral habitats.
Protect natural areas. Expand wildlife corridors, flyways, and greenways.
Increase populations of protected and other native species.
Determine impacts of changes in habitat and environmental conditions on recruitment, growth, and survival.
INFORMATION NEEDS
Historical relationship of surface and groundwater flows through the Everglades, flow restriction through Keys channels, and Florida Bay salinity.
Effects of climate extremes on accumulation of sediments, nutrients, and organic matter in Florida Bay.
Effects of increased water residence time in Florida Bay caused by restricted Keys channel flow, shoaling, and reduced freshwater inflows.
Quantitative data on inputs and outputs for nutrient budget.
Nutrient exchange rates between sediment, water column, and plants.
Controls on magnitude and flux directions.
Phytoplankton, macroalgal, and coral nutrient assimilation rates.
Sources, quantities, and effects of toxic pollutants.
Cause of turbidity in Florida Bay and relation to water quality.
Principal environmental factors that explain observed distribution and recent die-off of seagrasses, corals, sponges, and mangroves.
Critical habitat.
Linkages between upland, coastal, and reef habitat.
Impacts of fragmentation on populations and processes.
Impacts of fragmentation.
Data necessary for recovery of endangered and threatened species.
Relationship of recruitment to habitat changes and distribution in estuaries and reef tract.
Relationship between altered conditions and growth and survival.
Relationship between habitat degradation/loss and fisheries productivity.
Relationship between Florida Bay habitat changes and changes in coral reefs and southern coastal areas.

Figure 16. Goal, objectives, and information needs for Subregion 8.

MAJOR ISSUES

The diversity of Subregion 8 is such that, while there is much information available on each habitat type, there is no synthesis of information on how these areas are linked either physically or biologically. In particular, neither the impact of adjacent waters (including fresh, estuarine, and oceanic) on the hydrography of the subregion nor the impact of these processes on the area's ecology are well described. Specifically, the following questions need to be addressed:

1. How will hydrological changes, both in quality and quantity of fresh, estuarine, and oceanic waters from all boundaries, impact coastal waters and associated habitats from Barnes Sound to Charlotte Harbor?

2. How will sea-level rise impact the area and interact with anthropogenic changes?

3. How does water quality from upstream subregions impact Subregion 8?

4. How will the hydrology of South Florida be affected by continued development in Monroe, Dade and Collier counties?

5. What are the main land-sea human interactions within the area?

Notably, a major issue is that 37 plant and animal species in Subregion 8 are Federally listed as endangered or threatened, or are under review for listing, under the Endangered Species Act of 1973 (Table 7). All 21 species currently listed either have recovery plans completed or in the process of completion.

EXISTING SCIENCE AND MANAGEMENT PLANS

Numerous plans have been developed or are already in place that address management of specific areas within Subregion 8. To determine the extent to which these plans address the critical questions above, all these plans were reviewed. Areas included under these existing plans are shown in Figure 17. The Interagency Science Plan for Florida Bay, which is in the process of implementation, is included as an appendix to this chapter because it addresses most of the total area within the subregion.

Interagency Science Plan for Florida Bay

This plan (Armentano et al. 1994) was developed for the estuarine and marine waters of Florida Bay and includes by definition the Florida Keys and the reef tract. The Federal and State agencies that have science and management responsibilities for this area are:

- Department of Interior (NPS/ENP, NBS, and USGS): responsibilities for Florida Bay proper;

- Department of Commerce (NOAA): responsibility for the FKNMS and marine endangered and protected species, including cetaceans and turtles;

- Florida Department of Environmental Protection: statutory responsibility for state waters and living marine resources in state waters; and

- South Florida Water Management District: statutory responsibility for upstream hydrology.

This document outlines a comprehensive science plan for Florida Bay with the goal of meeting the criteria for ecological restoration. The review of historical information has resulted in identification of information gaps which, in turn, results in identification of science information needs. These needs are couched around a series of 14 questions originally presented in the Draft ENP research plan for Florida Bay (Robblee et al. 1993); the Boesch et al. report (1993); a NOAA workshop report on Florida Bay (Ortner et al. 1993); and internal working documents for the FDEP, SFWMD, and USGS.

Table 7. Status of endangered and threatened species in Subregion 8. END = Endangered, THR = Threatened, UR = Under Review, THR(S/A) = Threatened by Similarity of Appearance, SSC = Species of Special Concern. based on Wood (1994) plus updated information from FWS.

	STATUS	
ANIMAL SPECIES	**FEDERAL**	**STATE** (if different from Federal)
American alligator	THR(S/A)	SSC
American crocodile	END	
Atlantic loggerhead turtle	THR	
Atlantic hawksbill turtle	END	
Atlantic green turtle	END	
Atlantic ridley Turtle	END	
Leatherback turtle	END	
Eastern indigo snake	THR	
Rimrock crowned snake	UR	THR
Piping plover	THR	
Southeastern snowy plover	UR	THR
White-crowned pigeon	UR	THR
Arctic peregrine falcon		END
Bald eagle	THR	
Wood stork	END	
Roseate tern	THR	
Key Largo cotton mouse	END	
Key Largo woodrat	END	
Silver rice rat	END	
Lower Keys marsh rabbit	END	
Key deer	END	
West Indian manatee	END	
Schaus' swallowtail butterfly	END	
PLANT SPECIES		
Blodgett's wild-mercury	UR	END
Big Pine partridge pea		THR
Prickly apple cactus	UR	END
Florida tree cactus	END	
Wild thyme spurge		END
Keys hairy-podded spurge	UR	END
Porter's broom spurge	UR	END
Garber's spurge	THR	END
Two-spike finger grass	UR	
Dollar orchid		END
Pineland privet	UR	
Pineland clustervine	UR	END
Sand flax	UR	END
Small-leaved cat tongue	UR	
Florida five-petaled leaf flower	UR	
Bloykin's few-leaved milkwort	UR	
Noseburn	UR	END
Florida gamagrass	UR	

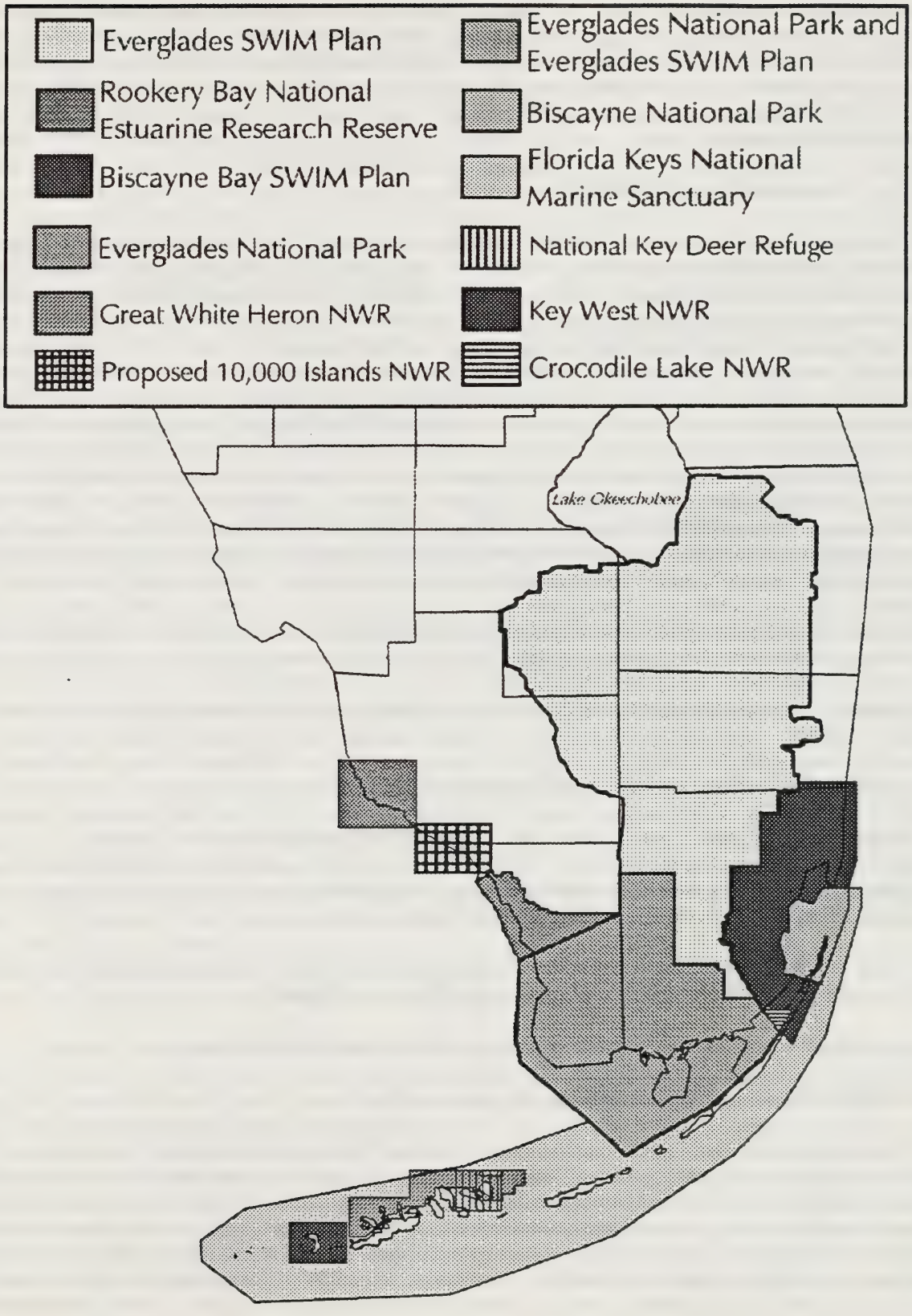


Figure 17. Areas included under science and management plans for Subregion 8.

Four major science topics were considered: 1) water budgets, circulation dynamics, and salinity; 2) water quality and nutrient cycling; 3) seagrass, mangrove, and hardbottom habitats; and 4) living resources and biodiversity. Based on the information reviewed relative to these topics, key science needs were identified under each topic. It was clearly noted that the impacts of changing the flow of water into the Bay on circulation dynamics, ecosystem dynamics, and living marine resources of the Bay and adjacent waters are not known. As noted in SSG (1993), the criteria for success in restoration are met primarily by restoring the ecology of the subregion and measured by the abundance, diversity, and viability of living resources. This plan addresses questions 1 and 3 relative to Florida Bay proper.

Water Quality Protection Plan for the FKNMS

This plan (CSA 1993) is a joint EPA/NOAA effort, as mandated to the EPA. It recognizes that reported degradation and changes in the various habitats are likely the result of the continued development of South Florida. Historically, freshwater input to the area was via rainfall. During the past century, the pattern and intensity of freshwater flows to South Florida estuaries were significantly affected by construction of the C&SF Project, which changed both hydrography and water quality. This plan notes that the impact on the FKNMS of hydrological changes in the Everglades is not known. The plan requires that a long-term strategy be developed to obtain information on the status of water quality and biological resources in the Sanctuary. The intention of this strategy is to allow for intervention and mitigation as needed to protect the FKNMS and its various communities. The plan indicates a suite of physical parameters will be monitored both in the water column and sediments. In addition, pollutants and nutrients will be monitored. Biological monitoring is based on a habitat approach using both *in situ* and remote methods. Changes in community quality and structure will be assessed. In addition to the EPA and NOAA, the plan recognizes that FDEP is responsible for establishing and maintaining the database that results. All five science questions are addressed by this plan relative to the FKNMS. While the plan currently identifies activities through FY98, activities are intended to be ongoing beyond this period. Major activities identified include:

- Develop phased hydrodynamic/water quality models and couple with landscape-level ecological models to predict and evaluate the outcome of alternative water quality management strategies;

- Develop a segmentation framework to identify surface water areas sharing common hydrographic properties effecting water quality;

- Identify and document causal linkages between water quality and ecological problems;

- Develop diagnostic indicators of water quality problems and identify and evaluate indicators;

- Identify and evaluate innovative monitoring tools and methodologies to detect pollutants and identify cause/effect relationships involving water quality and biological resources;

- Work with appropriate agencies regarding hydrology of South Florida and impacts on Florida Bay and the FKNMS and conduct research on impact of flow from the Bay on the FKNMS; and

- Examine effects of global climate change on organisms and ecosystems of the Keys.

FKNMS Draft Environmental Impact Statement/Management Plan

This plan (NOAA 1994) is the umbrella under which the Water Quality Protection Plan is included. The same types of information relative to the pre- and post-drainage Everglades and the impact of drainage on the FKNMS are included. However, in addition to addressing the issues of hydrology, water quality and hydrography and related scientific studies, it includes strategies relative to boating, recreation, and land use. One result of this plan was development of the Marine Reserve strategy now under consideration. This strategy will result in establishment of areas where only nonconsumptive use of resources is allowed. This plan points out the advantages of a Sanctuary for managing resources to minimize negative human impacts, while still allowing multiple uses.

Surface Water Improvement and Management Plan for Biscayne Bay

This SWIM Plan update (Alleman et al. 1995a,b) presents a comprehensive program to strengthen the well established effort to protect and enhance Biscayne Bay. The plan encompasses the area east of the L-30/L-31N/L-31W levee system and the C-111 canal and extends from just north of the Dade/Broward county line south to ENP and U.S. Highway 1 to Key Largo, including Card and Barnes sounds. Historically, the area received freshwater sheet flow from the Everglades. Over the past century, drainage of the Everglades, construction of the Intracoastal Waterway, and continued development has resulted in reduced circulation, increased turbidity, habitat destruction, and altered salinity patterns. The SWIM Plan addresses the multitude of problems and issues related to water quality and its impacts on diverse habitats and how to ameliorate these to meet the SWIM legislation and FDEP regulations. The two major issues addressed are water quality and freshwater inflow and the impacts of these on living resources and habitat. It is noted that the pulsed nature of large freshwater input from canals has had major negative impacts on Biscayne Bay and its structure. The plan in particular notes the importance of preserving upland communities, which act as filters for freshwater inputs into the Bay and are critical for maintenance of water quality. There are 24 recommendations that relate to improving and maintaining water quality and quantity into Biscayne Bay and the impacts of these on its physical and ecological dynamics and properties. All five questions are addressed by this plan for Biscayne Bay.

The West Florida Shelf: Past, Present, and Future

This document (FIO 1992) presents results of a workshop hosted by the Florida Institute of Oceanography in 1992; sponsors included FDEP, EPA, and NOAA. Subregion 8 is subsumed in the entire area of concern of this workshop, which was convened to review information and develop an integrated approach to continued research in support of management. Surface circulation of the area is dominated by the Loop Current, which exits through the Florida Straits (Keys) to form the Florida Current and then the Gulf Stream. Position of these currents is traditionally determined via temperature and depth. It is noted that coastal intrusions of the Loop Current have significant impact on coastal waters and are both spatially and temporally unpredictable and result in upwelling. Wind is also known to generate coastal movement and entrapment of current water. These processes are hypothesized to propagate cold, high salinity, nutrient-rich water into the coastal zone and catalyze red tides. The WFS circulation within Subregion 8 is characterized by a coastal regime influenced by the estuaries upstream and within the area including Tampa Bay and Charlotte Harbor in addition to the tidal and wind forced processes. The report describes the southern area of the WFS as a distinct subregion coupled to the northern areas. The southern area is within Subregion 8 from Florida Bay to the Keys and is described as an area of carbonate sediments, coastal mangroves, seagrasses, and coral reefs. Scientific studies in this area focus on physical characteristics, including hydrography and geology, and the resulting ecology. Physical, geological, chemical, and biological studies have extended from the Florida Keys through Florida Bay providing information for the southern system. Upstream influences from freshwater inputs are unknown particularly as related to the alternative hydrology of the Everglades. Waters within Subregion 8 are transported via the Gulf Stream along the Atlantic coast, and the impact of these waters (quality) is not known.

Surface Water Improvement and Management Plan for the Everglades

This plan (VanArman et al. 1989) describes activities relative to improving water quality in the Everglades, including Florida Bay. Florida Bay is described as extending from Barnes Sound to Long Key Basin and north through Whitewater Bay and adjacent coastal swamps and lagoons. The C&SF Project has resulted in water quality changes that have impacted the diverse habitats within the Bay. In particular, water quality problems appear to exist in the Central Bay, in Barnes Sound and Manatee Bay, and in the basins and sounds along the shoreline of the Florida Keys. These problems are due in part to hypersaline conditions that now exist. The shoreline of the Keys is identified as an area of particular concern that requires additional protection. The major information needs for Subregion 8 are included in this plan; those not addressed have been incorporated into the Interagency Science Plan for Florida Bay. The Everglades SWIM Plan has been superseded by the 1994 Florida Everglades Forever Act, which enables implementation of the cleanup program embodied in the SWIM Plan (SFWMD 1994).

Environmental Characterization of Rookery Bay National Estuarine Research Reserve: Phase I

This report (Smith 1993) reviews over 130 documents on Rookery Bay. This Collier County estuary is part of the NERR System and managed jointly by NOAA and FDEP. It extends from Marco Island to Naples and is characterized by upland habitats, mangrove forests (dominant habitat type), freshwater ponds, both fresh and salt marshes, mudflats, oyster bars, and seagrass beds. Research directed at physical, chemical, and biological characteristics and processes began in the early 1970s. The largest and most extensive database relates to water quality studies, which have been conducted annually since 1970. Monitoring has focused on birds and pesticides in mangrove forests, leading to mangrove restoration efforts. Within estuarine waters, monitoring has focused on manatees and fisheries resources. It is anticipated water quality will change as a result of human impacts upstream from the estuary. These human impacts include development to accommodate 125 new residents per week and increasing agriculture. Naples was described as the fastest growing area in the U.S in the 1980s, and the impact of continued growth is not known. Determining and predicting spatial and temporal patterns of freshwater inflow is critical to Rookery Bay NERR management.

NOAA Florida Bay Implementation Plan

By defining what NOAA is currently doing in Florida Bay, this document (NOAA 1995) is the first such plan that identifies scientific projects underway and those proposed specifically to address science needs for Florida Bay. The plan is designed to address those science needs stated in the Interagency Science Plan for Florida Bay by applying NOAA's expertise to answer specific science questions. The sum of the implementation plans for each agency reflect the science needs identified in the Interagency Science Plan for Florida Bay.

Management Agreement for Backcountry Portions of Key West National Wildlife Refuge, Great White Heron National Wildlife Refuge, and National Key Deer Refuge

This plan (FWS/FDNR 1992) between the FWS and State of Florida provides the framework for establishment and use of the NWRs of the Florida Keys and Florida Bay. While this plan outlines uses and regulations for these refuges, it neither addresses science nor represents a comprehensive strategic plan for the refuges as a whole.

INFORMATION NEEDS

1. Each agency needs to develop an implementation plan, relative to their jurisdictional responsibilities, that addresses the scientific information needs outlined in Figure 16. Plans need to not only be complementary and supplementary in scope, but should also be coordinated to minimize inefficient redundancy.

2. A complete biological inventory of Subregion 8 must be completed by the agency with primary jurisdictional responsibility for each area within the subregion. Monitoring of all endangered and threatened species must be continued to ensure recovery.

3. The FWS needs to develop a comprehensive strategic plan that includes all wildlife refuges as a whole, within the subregion and perhaps within the State. A science implementation plan must also be developed that includes impacts of continued development on habitat, especially as related to endangered species. Science priorities include: a) determining ecology and status of the Key deer and impacts of habitat loss or change on population status and condition; b) impact of prescribed burning on habitat, especially determining when and how frequently burning needs to be completed if at all; c) an inventory of species with emphasis on endangered species and determination of candidate species for listing under the ESA.

4. Linkages between upland influences relative to coastal habitat need to be better defined and identified in all existing plans.

BIBLIOGRAPHY

Adams, S.M. 1976. The ecology of eelgrass, *Zostera marina*, fish communities. I. Structural analysis. Journal of Experimental Marine Biology and Ecology 22:269-291.

Alleman, R.W., S.A. Bellmund, D.W. Black, S.A. Formati, C.A. Gove, L.K. Gulick, et al. 1995a. An update of the Surface Water Improvement and Management Plan for Biscayne Bay: Technical supporting document and appendices. Planning Department, SFWMD, West Palm Beach, Florida.

Alleman, R.W., D.W. Black, S.E. Formati, L.K. Gulick, and J.A. VanArman. 1995b. An update of the Surface Water Improvement and Management Plan for Biscayne Bay: Planning document. Planning Department, SFWMD, West Palm Beach, Florida.

Anonymous. 1992. Catastrophic mortality of sponges affects juvenile spiny lobster populations. The Lobster Newsletter 5(2):1-2.

Appeldoorn, R., J. Beets, J. Bohnsack, S. Bolden, D. Matos, S. Meyers, A. Rosario, Y. Sadovy, and W. Tobias. 1992. Shallow water reef fish stock assessment for the U.S. Caribbean. NOAA Technical Memorandum No. NMFS-SEFSC-304. NMFS, Miami, Florida.

Armentano, T.V., M. Robblee, P. Ortner, N. Thompson, D. Rudnick, and J. Hunt. 1994. Science Plan for Florida Bay. Interagency Working Group on Florida Bay (NPS, NBS, NOAA, SFWMD, and FDEP).

Ault, J.S. 1992. Age-structured abundance/density equations for tropical multicohort populations. Proceedings of the Gulf and Caribbean Fisheries Institute 41:245-273.

Barber, T.R. and P.R. Carlson Jr. 1993. Effects of seagrass die-off on benthic fluxes and porewater concentrations of CO_2, H_2S, and CH_4 in Florida Bay sediments. Pages 530-550 *in* R.S. Oremland, editor. Proceedings of the 10th Annual Meeting of the International Society of Environmental Biogeochemistry.

Beaver, R.W. 1988. Comments on the market category bottom fish. FMRI in-house report.

Beaver, R.W. 1988. Observations on the seasonality of mangrove snapper, dolphin, pompano and mullet landings in the Florida Keys. FMRI in-house report.

Beaver, R.W. 1988. Results from monitoring the spiny lobster, *Panulirus argus*, fishery in the Florida Keys: 1987/88 season. FMRI inhouse report.

Beaver, R.W. 1989. Results from monitoring the 1988/89 commercial lobster season in the Florida Keys. FMRI inhouse report.

Beaver, R.W. 1990. Commercial fishing in the Florida Keys: 1989. FMRI inhouse report.

Beaver, R.W., and N. Parrack. 1994. Biometrics conversion formulae for greater amberjack from South Florida. Manuscript.

Berg, C.J. Jr., and R.A. Glazer. 1990. Stock assessment of the queen conch in Florida waters: executive summary. Report to the Florida Marine Fisheries Commission.

Berg, C.J. Jr., and R.A. Glazer. 1991. Current research on queen conch, *Strombus gigas*, in Florida waters. Proceedings of the Gulf and Caribbean Fisheries Institute 40:303-306.

Berg, C.J. Jr., and R.A. Glazer. In press. Stock assessment of a large marine gastropod (*Strombus gigas*) using randomized and stratified towed-diver censuring. Rapp. P.-V. Réun. Cons. Int. Explor. Mer.

Berg, C.J. Jr., R.A. Glazer, J. Carr, J. Krieger, and S. Acton. 1992. Status of the queen conch, *Strombus gigas*, in Florida waters: a progress report. Proceedings of the Gulf and Caribbean Fisheries Institute 41:439-443.

Berkeley, S.A., D.W. Pybas, and W.L. Campos. 1985. Bait shrimp fishery of Biscayne Bay. Florida Sea Grant College Technical Paper No. 40.

Bert, T.M., J. Tilmant, J. Dodrill, and G.E. Davis. 1986. Aspects of the population dynamics and biology of the stone crab (*Menippe mercenaria*) in Everglades and Biscayne National Parks as determined by trapping. Report SFRC-86/04. SFRC, ENP, Homestead, Florida.

Bertelsen, R.D. In review. The recreational harvest of the Florida spiny lobster (*Panulirus argus*): results of the 1992 mail surveys. FDNR Report.

Bertelsen, R.D., and J.H. Hunt. 1992. Results of the 1991 mail surveys of recreational lobster fishermen (special sport season and regular season surveys). FDNR Report.

Blonder, B.I., J.H. Hunt, D. Forcucci, and W.G. Lyons. 1988. Effects of recreational and commercial fishing on spiny lobster abundance at Looe Key National Marine Sanctuary. Proceedings of the Gulf and Caribbean Fisheries Institute 41:487-507.

Boesch, D.F., N.E. Armstrong, C.F. D'Elia, N.G. Maynard, H.W. Paerl, and S.L. Williams. 1993. Deterioration of the Florida Bay ecosystem: an evaluation of scientific evidence. Report of Florida Bay Scientific Review Panel to Interagency Working Group Report on Florida Bay.

Bohnsack, J.A. 1976. An investigation of a photographic method for sampling hard-bottom benthic communities. Master's thesis. UM, Coral Gables, Florida.

Bohnsack, J.A. 1976. The spider crab, *Mithrax spinosissimus*: an investigation including commercial aspects. Florida Scientist 39(4):259-266.

Bohnsack, J.A. 1979. The ecology of reef fishes on isolated coral heads: An experimental approach with emphasis on island biogeographic theory. Ph.D. dissertation. UM, Coral Gables, Florida.

Bohnsack, J.A. 1982. The effects of piscivorous predator removal on coral reef fish community structure. Pages 258-267 *in* 1981 Gutshop: Third Pacific Technical Workshop Fish Food Habits Studies. Washington Sea Grant Publication.

Bohnsack, J.A. 1983. Draft resources studies plan: Looe Key National Marine Sanctuary. Prepared for James Dobbin Associates and Sanctuary Programs Office, Office of Coastal Zone Management, U.S. Department of Commerce. NMFS, Miami, Florida.

Bohnsack, J.A. 1983. Resiliency of reef fish communities in the Florida Keys following a January 1977 hypothermal fish kill. Environmental Biology of Fishes 9:41-53.

Bohnsack, J.A. 1983. Species turnover and the order versus chaos controversy concerning reef fish community structure. Coral Reefs 1:223-228.

Bohnsack, J.A. 1984. Resiliency of coral reef fish community structure in response to reduced harvesting pressure. Final report, NOAA Postdoctoral Fellowship. Office of University Affairs, NOAA.

Bohnsack, J.A., editor. 1985. Final report: resource survey of Looe Key National Marine Sanctuary, phase I. Report prepared for the Sanctuary Programs Division, Office of Ocean and Coastal Resource Management, NOAA.

Bohnsack, J.A. 1989. Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? Bulletin of Marine Science 44:631-645.

Bohnsack, J.A. 1989. Protection of grouper spawning aggregations. Report for the Caribbean Fishery Management Council. Coastal Resource Division Contribution No. CRD-88\89-06. NMFS, Miami, Florida.

Bohnsack J.A. 1989. The impact of overfishing on tropical fisheries. Pages 35-49 *in* de Graaf and Moore, editors. Proceedings of the Conference on Fisheries in Crisis, 24-25 September 1987. Department of Planning and Natural Resources, Fish and Wildlife Division, St. Thomas, Virgin Islands.

Bohnsack, J.A. 1990. Black and nassau grouper fishery trends. Report to the South Atlantic Fishery Management Council.

Bohnsack, J.A. 1990. Progress report: Biscayne National Park reef fish survey, January 1990. Report to NPS.

Bohnsack, J.A., subcommittee chair. 1990. The potential of marine fishery reserves for reef fish management in the U.S. southern Atlantic. Snapper-Grouper Plan Development Team Report for the South Atlantic Fishery Management Council. NOAA Technical Memorandum NMFS-SEFC-261. NMFS, Miami, Florida.

Bohnsack, J.A. 1992. The ecological basis for using marine fishery reserves for reef resource management. Proceedings of the First Annual Coral Reef Coalition Conference 1992:15-24.

Bohnsack, J.A. 1993. The impacts of fishing on coral reefs. Pages 201-207 *in* R.N. Ginsburg, compiler. Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards, and History. UM, 10-11 June 1993, Coral Gables, Florida.

Bohnsack, J.A. 1994. Marine reserves: they enhance fisheries, reduce conflicts, and protect resources. NAGA, The ICLARM Quarterly 17(3):4-7.

Bohnsack, J.A., and J.S. Ault. In press. Management strategies to conserve marine biodiversity. Oceanography 9.

Bohnsack, J.A., A. Brown, M. Collins, J. Halusky, D. Harper, B. Hermkind, R. Holhberg, M. Hulsbeck, J. Kimmel, D. McClellan, M. McGowan, J. Ogden, B. Seaman, and D. Sutherland. 1989. Report of the working group on reef and benthic fisheries. Pages 23-28 *in*: G.S. Kleppel and W. Seaman Jr., editors. Fishery Recruitment in Florida Waters. Florida Sea Grant Technical Paper No. 57.

Bohnsack, J.A., A. Brown Jr., D. Matos, and S. Meyers. 1994. Stock assessment of spiny lobster in the U.S. Caribbean I. 1990 data base review and length frequency analysis. Proceedings of the Gulf and Caribbean Fisheries Institute, 1990 (non-peer-review section) 43:624-646.

Bohnsack, J.A., and P. Fischel. In review. Synopsis of biological data on the hogfish, *Lachnolaimus maximus* (Pisces: Labridae). NOAA Technical Report NMFS Circular: FAO Fisheries Synopsis No. 000.

Bohnsack, J.A., and D.E. Harper. 1988. Length-weight relationships of selected marine reef fishes from southeastern United States and the Caribbean. NOAA Technical Memorandum NMFS-SEFC-215. NMFS, Miami, Florida.

Bohnsack, J.A., D.E. Harper, D.B. McClellan, and M. Hulsbeck. 1989. The relative importance of recruitment, attraction, and production of reef fishes on natural and modular artificial reefs. Preliminary final report to Florida Sea Grant. NMFS, Miami, Florida.

Bohnsack, J.A., D.E. Harper, D.B. McClellan, and M. Hulsbeck. 1994. Effect of reef size on recruitment and assemblage structure of fishes at artificial reefs off southeastern Florida, U.S.A. Bulletin of Marine Science 55(2):798-825.

Bohnsack, J.A., D.E. Harper, D.B. McClellan, M.W. Hulsbeck, T.N. Rutledge, M.H. Pickett and A.M. Eklund. 1992. Quantitative visual assessment of fish community structure in Biscayne National Park. Draft final report. NMFS, Miami, Florida.

Bohnsack, J.A., D.E. Harper, D.B. McClellan, D.L. Sutherland, and M.W. White. 1987. Resource survey of fishes within Looe Key National Marine Sanctuary. NOAA Technical Memorandum NOS MEMD 5:1-108.

Bohnsack, J.A., S. Meyers, R. Appeldoorn, J. Beets, D. Matos, and Y. Sadovy. 1991. Stock assessment of spiny lobster, *Panulirus argus*, in the U.S. Caribbean. Report to the Caribbean Fishery Management Council. Miami Laboratory Contribution No. MIA-90/91-49. NMFS, Miami, Florida.

Bohnsack, J.A., D.L. Sutherland, D.E. Harper, D.B. McClellan, M.W. Hulsbeck, and C.M. Holt. 1989. The effects of fish trap mesh size on reef fish catch off southeastern Florida. Marine Fisheries Review 51(2):36-46.

Bright, T.J., W.C. Jaap, and C.W. Cashman. 1981. Ecology and management of coral reefs and organic banks. Pages 53-159 *in* D.K. Atwood, convener. Proceedings of a Symposium on Environmental Research Needs in the Gulf of Mexico (GOMEX), Key Biscayne, Florida, 30 September--5 October 1979. Volume IIB. NOAA Atlantic Oceanographic and Meteorological Laboratories, Miami, Florida.

Brock, R.J., J.C. Cato, and W. Seaman, organizers. 1995. Florida Bay Science Conference: A Report by Principal Investigators, October 17 & 18, 1995, Gainesville, Florida. Abstracts and program. NPS, NBS, NOAA, USGS, FWS, COE, FKNMS, FDEP, and SFWMD.

Browder, J.A.. 1985. Relationship between pink shrimp production on the Tortugas grounds and water flow patterns in the Florida Everglades. Bulletin of Marine Science 37(3):839-856.

Browder, J., C. Littlejohn, and D. Young. 1976. South Florida: seeking a balance of man and nature. UF, Gainesville, Florida.

Bulletin of Marine Science. 1989. Symposium on Florida Bay, A Subtropical Lagoon, U.S. National Park Service/Everglades National Park and University of Miami/Rosenstiel School of Marine and Atmospheric Science, 1-5 June 1987. Bulletin of Marine Science 44(1):1-526.

Bulletin of Marine Science. 1994. Symposium on Florida Keys Regional Ecosystem, November 1992. Bulletin of Marine Science 54(3):577-1088.

Butler, M.J. IV, and W.F. Herrnkind. 1988. Spiny lobster recruitment in South Florida: quantitative experiments and management implications. Proceedings of the Gulf and Caribbean Fisheries Institute 41:508-515.

Butler, M.J. IV, and W.F. Herrnkind. 1989. Are artificial "Witham" surface collectors adequate indicators of Caribbean Spiny Lobster, *Panulirus argus*, recruitment? Proceedings of the Gulf and Caribbean Fisheries Institute 42:135 -138.

Butler, M.J. IV, and W.F. Herrnkind. 1991. Effect of benthic microhabitat cues on the metamorphosis of pueruli of the spiny lobster, *Panulirus argus*. Journal of Crustacean Biology 11:23-28.

Butler, M.J. IV, J.H. Hunt, W.F. Herrnkind, M. Childress, R. Bertelsen, W. Sharp, T. Matthews, J.M. Field, and H.G. Marshall. 1995. Cascading disturbances in Florida Bay (USA): cyanobacteria blooms, sponge mortality, and implications for juvenile spiny lobsters, *Panulirus argus*. Marine Ecology Progress Series 129:119-125.

Campos, W.L. 1985. Distribution patterns of juvenile epibenthic fish in south Biscayne Bay, Florida. M.S. thesis. UM, Coral Gables, Florida.

Campton, D.E., L. Robison, C.J. Berg Jr, and R.A. Glazer. 1992. Genetic patchiness among populations of queen conch *Strombus gigas* in the Florida Keys and Bimini. Fishery Bulletin 90:250-259.

Campton, D.E., L. Robison, C.J. Berg Jr, and R.A. Glazer. In press. Deficits of heterozygotes and correlation between body size and heterozygosity in another marine mollusk, *Strombus gigas* (Gastropoda: Strombidae). Evolution.

Cantillo, A.Y., T.P. O'Connor, and G.G. Lauenstein. 1993. South Florida environmental quality. NOAA Technical Memorandum NOS ORCA 75. NOAA, Silver Spring, Maryland.

Cantillo, A.Y., L. Pikula, J. Beattie, E. Collins, K. Hale, and T. Schmidt. 1995. Natural and anthropogenic events impacting Florida Bay, 1910 - 1994 time line. NOAA Technical Memorandum NOS ORCA 90. NOAA, Silver Spring, Maryland.

Carey, R.C., P.S. Markovits, and J.B. Kirkwood, editors. 1981. Proceedings U.S. Fish and Wildlife Service Workshop on Coastal Ecosystems of the Southeastern United States. FWS/OBS-80/59. FWS, Washington, D.C.

Carins, S.D., D.R. Calder, A. Brinckmann-Voss, C.B. Castro, P.R. Pugh, C.E. Cutress, W.C. Jaap, D.G. Fautin, R.J. Larson, G.R. Harbison, M.N. Arai, and D.N. Opresko. 1991. Common and scientific names of aquatic invertebrates from the United States and Canada: Cnidaria and Ctenophora. American Fisheries Society Special Publication 22.

Carlson, P.R., M.J. Durako, T.R. Barber, L.A. Yarbro, Y. deLama, and B. Hedin. 1990. Catastrophic mortality of the seagrass *Thalassia testudinum* in Florida Bay. Annual completion report, Grant CM-257. FDER.

Carlson, P.R., and L.A. Yarbro. 1988. Physical and biological control of mangrove pore water chemistry. Pages 112-131 *in* D.D. Hook et al., editors. The Ecology and Management of Wetlands, Vol. 1, Ecology of Wetlands. Timber Press, Portland, Oregon.

Causey, B., J.C. Halas, J.H. Hudson, and W.C. Jaap. 1988. Zooxanthellae expulsions in Florida reefs during 1987. Proceedings of the Association of Island Marine Laboratories of the Caribbean (1988)21:51 (abstract).

Chester, A.J., and G.W. Thayer. 1990. Distribution of spotted seatrout (*Cynoscion nebulosus*) and gray snapper (*Lutjanus griseus*) juveniles in seagrass habitats of western Florida Bay. Bulletin of Marine Science 46:345-357.

Chow, S., M.E. Clarke, and P.J. Walsh. 1993. PCR-RFLP analysis on thirteen western Atlantic snappers (subfamily Lutjaninae): a simple lmethod for species and stock identification. Fishery Bulletin 91:619-627.

Chow, S., and P.J. Walsh. 1992. Biochemical and morphometric analyses for phylogenetic relationships between seven snapper species (subfamily Lutjaninae) of the western Atlantic. Bulletin of Marine Science 50:508-519.

Clark, J.R., B. Causey, and J.A. Bohnsack. 1989. Benefits from coral reef protection: Looe Key Reef, Florida. Coastal Zone '89 (Proceedings 6th Symposium on Coastal and Ocean Management) 4:3076-3086.

Clarke, M.E., C. Calvi, M. Domeier, M. Edmonds, and P.J. Walsh. 1988. Effects of nutrition and temperature on enzyme activities in larval and juvenile red drum, *Sciaenops ocellatus* and lane snapper, *Lutjanus synagris*. Marine Biology 112:31-36.

Clarke, M.E. and M.L. Domeier. Submitted. Description of larvae and early juveniles of two laboratory-reared snappers, Lane snapper, *Lutjanus synagris* (Linnaeus), yellowtail snapper, *Ocyurus chrysurus* (Bloch) and a description of a laboratory produced intergeneric hybrid of *Ocyurus chrysurus* and *Lutjanus synagris*.

Clarke, M.E., and T.N. Lee. 1992. Influence of recirculation features, wind-driven transport and larval growth on the recruitment of fish larvae in the Florida Keys. EOS Transactions, AGU 72(51):66.

Clarke, M.E., and A. Szmant. Undated. SEFCAR data report: nutrient and chlorophyll values for SEFCAR 1989-1990. RSMAS, Miami, Florida.

Clarke, M.E., and P.J. Walsh. 1993. Effect of nutritional status on citrate synthase activity in *Acartia tonsa* and *Temora longicornis*. Limnology and Oceanography 38(2):414-418.

Colby, D.R., G.W. Thayer, W.F. Hettler, and D.S. Peters. 1985. A comparison of forage fish communities in relation to habitat parameters in Faka Union Bay, Florida and eight collateral bays during the wet season. NOAA Technical Memorandum NMFS-SEFC-162. NMFS, Beaufort, North Carolina.

Conley, W.J., and B.A. Hoffman. 1987. Nesting activity of sea turtles in Florida, 1979-1985. Florida Scientist 50:201-210.

Continental Shelf Associates. 1993. Water Quality Protection Program for the Florida Keys National Marine Sanctuary. Draft program document. EPA Contract No. 68-C8-0134. CSA, Jupiter, Florida.

Couillard, T. 1992. A model of visible spectral subsurface irradiance with reference to control of vertical migration of zooplankton. M.A. thesis. UM, Coral Gables, Florida.

Cox, J., R. Kautz, M. MacLaughlin, and T. Gilbert. 1994. Closing the Gaps in Florida's Wildlife Habitat Conservation System. Office of Environmental Services, FGFFC, Tallahassee, Florida.

Criales, M.M., and T.N. Lee. 1995. Larval distribution and transport of penaeoid shrimps during the presence of the Tortugas Gyre in May-June 1991. Fishery Bulletin 93:471-482.

Criales, M.M., and M.F. McGowan. 1993. Coastal-oceanic planktonic distribution of natantia shrimps in the Florida Keys, U.S.A. Revista de Biologia Tropical, Suplemento 41(1):23-26.

Criales, M.M., and M.F. McGowan. 1993. Occurrence and description of mysis larvae of a mesopelagic shrimp species of the genus *Gennades* (Crustacea:Decapoda:Aristeidae) from coastal waters of South Florida. Bulletin of Marine Science 53(3):973-984.

Crosby, M.P. 1994. Opportunities for nonindigenous species research and monitoring in NOAA's National Estuarine Research Reserves. Pages 69-78 *in* Proceedings of the Nonindigenous Estuarine and Marine Organism Conference, Seattle, Washington, April 1993. NOAA, Washington, D.C.

Crosby, M.P. 1994. A proposed approach for studying ecological and socio-economic impacts of alternative access management strategies in marine protected areas. Pages 45-65 *in* D.J. Brunkhorst, editor. Marine Protected Areas and Biosphere Reserves: 'Towards a New Paradigm'. Australian Nature Conservation Agency, Canberra, Australia.

Crosby M.P., and A.D. Beck. 1995. Management-oriented research in National Estuarine Research Reserves, with examples of fisheries-focused studies. Natural Areas Journal 15:12-20.

Crosby, M. P., S.F. Drake, C.M. Eakin, N.B. Fanning, A. Paterson, P.R. Taylor, and J. Wilson. 1995. The United States Coral Reef Initiative: an overview of the first steps. Coral Reefs 13: 249-251.

Crosby, M.P., and H.M. Golde. 1993. A review and synthesis of the first decade of research in the National Estuarine Research Reserve System. Technical Memorandum No. 26. Office of Ocean and Coastal Resource Management, National Ocean Service, NOAA, Washington, D.C.

Davis, C.C. 1948. Notes on the plankton of Long Lake, Dade county, Florida, with descriptions of two new copepods. Quarterly Journal of the Florida Academy of Sciences 10(2/3):79-88.

Davis, G.E., and M.C. Whiting. 1977. Loggerhead sea turtle nesting in Everglades National Park, Florida, USA. Herpetologica 33:18-28.

Day, J.W., and A. Yanez-Arancibia. 1985. Coastal lagoons and estuaries as an environment for nekton. Pages 17-34 (Chapter 3) *in* A. Yanez-Arancibia, editor. Fish Community Ecology in Estuaries and Coastal Lagoons: Towards an Ecosystem Integration. UNAM Press Mexico.

DeSylva, D.P. 1975. Nektonic food webs in estuaries. Pages 420-447 *in* Chemistry, Biology and the Estuarine System. Estuarine Research Volume 1. Academic Press.

DeSylva, D.P. 1976. Ecology and distribution of post-larval fishes in southern Biscayne Bay, Florida. Final report to EPA Division of Water Quality Research.

DeSylva, D.P. 1976. Fishes of Biscayne Bay. Pages 181-202 *in* A.L. Thorhaug and A.S. Volker, editors. Biscayne Bay: Past/Present/Future. UM Sea Grant Program Special Report 5.

Domeier, M.L. 1992. Speciation in the serranid fish *Hypoplectrus*. Ph.D. dissertation. UM, Coral Gables, Florida.

Domeier, M.L., and M.E. Clarke. 1992. A laboratory produced hybrid between *Lutjanus synagris* and *Ocyurus chrysurus* and a probable hybrid between *L. griseus* and *O. chrysurus* (Perciformes: Lutjanidae). Bulletin of Marine Science 50:501-507.

Durako, M.J. 1988. Turtle grass (*Thalassia testudinum* Banks ex Konig) - a seagrass. Pages 504-520 *in* Y.P.S. Bajaj, editor. Biotechnology in Agriculture and Forestry, Volume 6, Crops II. Springer-Verlag, New York.

Durako, M.J. 1994. Indicators of seagrass ecological condition: an assessment based on spatial and temporal changes. Pages 261-266 *in* K.R. Dyer and R.J. Orth, editors. Changes in Fluxes in Estuaries: Implications from Science to Management. Proceedings of ECSA 22/ERF Symposium, 13-18 September 1992, University of Plymouth, U.K. Olsen & Olsen, Fredensborg, Denmark.

Durako, M.J. 1994. Seagrass die-off in Florida Bay (USA) - changes in shoot demographic characteristics and population dynamics in *Thalassia testudinum*. Marine Ecology Progress Series 110(1):59-66.

Durako, M.J., T.R. Barber, J.B.C. Bugden, P.R. Carlson, J.W. Fourqurean, R.D. Jones, D. Porter, M.B. Robblee, L.A. Yarbro, R.T. Zieman, and J.C. Zieman. 1993. Seagrass die-off in Florida Bay. Pages 14-15 *in* J.D. Jacobsen, editor. America's Sea - Keep It Shining. Proceedings of 1992 Gulf of Mexico Symposium, December 10-12, 1992, Tarpon Springs, Florida. Gulf of Mexico Program Office, John C. Stennis Space Center, Stennis, Mississippi.

Durako, M.J., R.C. Phillips, and R.R. Lewis, editors. 1987. Proceedings of the Symposium on Subtropical-Tropical Seagrasses of the Southeastern United States. Florida Marine Research Publication No. 42. FMRI, St. Petersburg, Florida.

Durako, M.J., and W.M. Sackett. 1991. Influence of carbon source on stable isotope composition of the seagrass *Thalassia testudinum*. Pages 453-462 *In* Proceedings of an International Symposium on the Use of Stable Isotopes in Plant Nutrition, Soil Fertility and Environmental Studies. International Atomic Energy Agency and the Food and Agriculture Organization of the United Nations, Vienna.

Durako, M.J., and W.M. Sackett. 1993. Effects of $CO_{2(aq)}$ on the carbon isotopic composition of the seagrass *Thalassia testudinum* Banks ex Kõnig (Hydrocharitaceae). Journal of Experimental Marine Biology and Ecology 169:167-180.

Ehrhardt, N.M., and J.S. Ault. 1992. Analysis of two length-based mortality models applied to bounded catch length frequencies. Transactions of the American Fisheries Society 121(1):115-122.

Environmental Science and Engineering, Inc., LGL Ecological Research Associates, Inc., and Continental Shelf Associates, Inc. 1987. Southwest Florida Shelf Ecosystems Study. 3 volumes. Minerals Management Service, New Orleans, Louisiana.

Facemire, C.F., and L. Chlebowski. 1991. Organochlorine pesticide and heavy metal contamination of American crocodile (*Crocodylus acutus*) eggs. FWS, Vero Beach, Florida.

Fausch, K.D., J. Lyons, J.R. Karr, and P.L. Angermeier. 1990. Fish communities as indicators of environmental degradation. American Fisheries Society Symposium 8:123-144.

Field, J.M., and M.J. Butler. 1994. The influence of temperature, salinity, and postlarval transport on the distribution of juvenile spiny lobsters, *Panulirus argus* (Latreille, 1804), in Florida Bay. Crustaceana 67(1):26-45.

Florida Department of Environmental Protection. 1995. Conservation and Recreation Lands 1995 annual report. Office of Environmental Services, FDEP, Tallahassee, Florida.

Florida Institute of Oceanography. 1992. The West Florida Shelf: Past, Present, and Future. Draft workshop report. FIO, St. Petersburg, Florida.

Fonseca, M.S. 1989. Regional analysis of the creation and restoration of seagrass systems. Pages 175-198 *in* J.A. Kusler and M.E. Kentula, editors. Wetland Creation and Restoration: The Status of the Science. Volume I - Regional Reviews. EPA/600/3-89/038a. EPA Environmental Research Laboratory, Corvallis, Oregon.

Fonseca, M.S. 1992. Restoring seagrass systems in the United States. Pages 79-110 (Chapter 3) *in* Restoring the Nation's Marine Environment. Publication UM-SG-TS-92-06. Maryland Sea Grant College, College Park, Maryland.

Fonseca, M.S. 1994. A guide to planting seagrasses in the Gulf of Mexico. TAMU-SG-94-601. Texas A&M University Sea Grant College Program.

Fonseca, M.S., W.J. Kenworthy, and G.W. Thayer. 1987. Transplanting of the seagrasses *Halodule wrightii*, *Syringodium filiforme*, and *Thalassia testudinum* for sediment stabilization and habitat development in the Southeast Region of the United States. Technical Report EL-87-8. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Fonseca, M.S., W.J. Kenworthy, and G.W. Thayer. 1992. Seagrass beds: nursery for coastal species. Pages 141-147 *in* R.H. Stroud, editor. Stemming the Tide of Coastal Fish Habitat Loss. Proceedings of a Symposium on Conservation of Coastal Fish Habitat, March 7-9, 1991, Baltimore, Maryland. Marine Recreational Fisheries 14. National Coalition for Marine Conservation, Inc., Savannah, Georgia.

Fourqurean, J.W., R.D. Jones, and J.C. Zieman. 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of biomass in Florida Bay, FL, USA: inferences from spatial distributions. Estuarine, Coastal and Shelf Science 36:295-314.

Fourqurean, J.W., and J.C. Zieman. 1991. Photosynthesis, respiration and whole plant carbon budgets of *Thalassia testudinum, Halodule wrightii and Syringodium filiforme*. Pages 59-70 *in* W.J. Kenworthy and D.E. Haunert, editors. The Light Requirements of Seagrasses. Proceedings of a Workshop to Examine the Capability of Water Quality Criteria, Standards and Monitoring Programs to Protect Seagrasses. NOAA Technical Memorandum NMFS-SEFC-287. NMFS, Beaufort, North Carolina.

Fritts, T.H., A.B. Irvine, R.D. Jennings, L.A. Collum, W. Hoffman, and A.M. McGehee. 1983. Turtles, birds, and mammals in the northern Gulf of Mexico and nearby Atlantic waters. FWS/OBS-82/65. FWS, Washington, D.C.

Gato, J., editor. 1991. The Monroe County Environmental Story. Monroe County Environmental Education Task Force, Big Pine Key, Florida.

Gilbes, F., C. Tomas, J.J. Walsh, and F.E. Muller-Karga. In press. An episodic chlorophyll plume on the West Florida Shelf. Continental Shelf Research.

Gilmore, R.G. and S.C. Snedaker. 1993. Mangrove Forests. Pages 165-198 (Chapter 5) *in* W.H. Martin, S.G Boyce and A.C. Echternacht, editors. Biodiversity of the Southeastern United States/Lowland Terrestrial Communities. John Wiley & Sons.

Glazer, R.A. 1990. A royal life isn't easy: queen of the Florida Keys. Archipelago 4(2):1-4.

Glazer, R.A. 1992. Inclusion of *Strombus gigas* in Appendix II of CITES. A report to the International Union of the Conservation of Nature and Natural Resources on the addition of queen conch to Appendix II of CITES thus recognizing the species as being in a regional decline.

Glazer, R.A., and C.J. Berg Jr. 1992. Growth and mortality of the queen conch, *Strombus gigas*, in Florida. Proceedings of the Gulf and Caribbean Fisheries Institute 42:153-157.

Glazer, R.A., and C.J. Berg Jr. In press. Queen conch research in Florida: an overview. *In* R.S. Appeldoorn, editor. Proceedings 1st Latin American Malacological Conference. Special Workshop on the Management and Culture of Queen Conch.

Glynn, P.W., P.K. Swart, and A. Szmant-Froelich, Technical Program Committee. 1984. Advances in Reef Sciences. Abstracts and Schedule of Presentations, A Joint Meeting of the Atlantic Reef Committee and The International Society for Reef Studies, October 26, 27, & 28, 1984. RSMAS, Miami, Florida.

Goldman, D.A., and M.F. McGowan. 1991. Distribution and abundance of ommastrephid squid paralarvae off the Florida Keys in August 1989. Bulletin of Marine Science 49(1-2):614-622.

Gorte, R.W. 1994. The Florida Bay economy and changing environmental conditions. Congressional Research Service Report for Congress 94-435 ENR. Library of Congress, Washington, D.C.

Gray, J.D., T.L. King, and R.L. Colura. 1991. Effect of temperature and hypersalinity on hatching success of spotted seatrout eggs. The Progressive Fish-Culturist 53:81-84.

Greene, L.E., and J.M. Shenker. 1993. The effects of human activity on the temporal variability of coral reef fish assemblages in the Key Largo National Marine Sanctuary. Aquatic Conservation: Marine and Freshwater Ecosystems 3:189-205.

Hale, K.K. 1993. Biscayne Bay: a bibliography of the marine environment. Technical Paper 67. Florida Sea Grant College Program, Gainesville, Florida.

Hallock, P., A.C. Hine, G.A. Vargo, J.A. Elrod, and W.C. Jaap. 1988. Platforms of the Nicaraguan Rise: examples of the sensitivity of carbonate sedimentation to excess trophic resources. Geology 16:1104-1107.

Hallock, P., W.C. Jaap, and K. Boomer Donnelly. 1990. Research diving on remote shoals of the Nicaraguan Rise, southwest Caribbean. Pages 139-145 *in* W. Jaap, editor. American Academy of Underwater Sciences Tenth Annual Scientific Diving Symposium, St. Petersburg, Florida, USA.

Hallock, P., G.A. Vargo, A.C. Hine, N.J. Triffleman, W.C. Jaap, and J.A. Elrod. 1988. Suppression of coral reef development by excess nutrients: examples on the Nicaraguan Rise. Proceedings of the Association of Island Marine Laboratories of the Caribbean (1988)21:60 (abstract).

Harper, D.E. 1993. The 1993 spiny lobster monitoring report on trends in landings, CPUE, and size of harvested lobster. NMFS, Miami, Florida.

Harper, D.E., J.A. Bohnsack, and D.B. McClellan. 1994. Investigation of bycatch from the wire-trap fishery in federal waters off southern Florida. Proceedings of the Gulf and Caribbean Fisheries Institute 43:3-25.

Harper, D.E., D.G. Neff, and J.A. Bohnsack. 1991. Florida Gulf Coast stone crab landings and fishing effort update, 1962-1990. Report to the Gulf of Mexico Fishery Management Council. Miami Laboratory Contribution No. MIA-90/91-79. NMFS, Miami, Florida.

Harris, B.A. W.J. Conley, and A.J. Huff. 1984. The status of Florida's nesting sea turtle populations from 1979 through 1983. Unpublished Report.

Harwell, C., editor. 1991. Report on the Research Planning Workshop for the Florida Keys National Marine Sanctuary, Miami, Florida, 7-9 October 1991. Sanctuaries and Reserves Division, NOAA, Washington, D.C., and RSMAS, Miami, Florida.

Heck, K.L., and R.J. Orth. 1980. Seagrass habitats: the role of habitat complexity, competition and predation in structuring associated fish and motile macroinvertebrate assemblages, I. Pages 449-464 *in* V.S. Kennedy, editor. Estuarine Perspectives. Academic Press, New York.

Herrnkind, W.F. 1994. Sponge and lobster research. FDEP-MRI Report C-8077. FMRI, St. Petersburg, Florida.

Herrnkind, W.F., and M.J. Butler. 1994. Settlement of spiny lobster, *Panulirus argus* (Latreille, 1804), in Florida: pattern without predictability? Crustaceana 67(1):46-64.

Herrnkind, W.F., M.J. Butler IV, and R.A. Tankersley. 1988. The effects of siltation on recruitment of spiny lobsters, *Panulirus argus*. Fishery Bulletin 86:331-338.

Hine, A.C., P. Hallock, M.W. Harris, H.T. Mullins, D.F. Belknap, and W.C. Jaap. 1988. *Halimeda* bioherms along an open seaway: Miskito Channel, Nicaraguan Rise, SW Caribbean Sea. Coral Reefs 6:173-178.

Hoss, D.E., and G.W. Thayer. 1993. The importance of habitat to the early life history of estuarine dependent fishes. American Fisheries Society Symposium 14:147-158.

Houde, E.D., and J.A. Lovdal. 1984. Seasonality of occurrence, foods and food preferences of ichthyoplankton in Biscayne Bay, Florida. Estuarine, Coastal and Shelf Science 18:403-419.

Huang, H. 1990. Holocene environmental history in a marginal marine area of the Everglades of South Florida. M.A. thesis. UM, Coral Gables, Florida.

Hudson, J.H., D.M. Allen, and T.J. Costello. 1970. The flora and fauna of a basin in central Florida Bay. FWS, Washington, DC.

Hudson, J.H., D.M. Robbin, J.T. Tilmant, and J.L. Wheaton. 1989. Building a coral reef in southeast Florida: combining technology and aesthetics. Bulletin of Marine Science 44(2):1067-1068 (abstract).

Hunt, J.H. 1992. Summary of lobster stamp holders response concerning use of recreational traps. FDNR Report.

Hunt, J.H., T.R. Matthews, D. Forcucci, B.S. Hedin, and R.D. Bertelsen. 1991. Management implications of trends in the population dynamics of the Caribbean spiny lobster, *Panulirus argus*, at Looe Key National Marine Sanctuary. NOAA Contract # 50-DGNC-6-00093.

Irvine, A.B., J.E. Caffin, and H.I. Kochman. 1981. Aerial surveys for manatees and dolphins in western peninsular Florida with notes on sighting sea turtles. FWS/OBS-80/50. FWS, Washington, D.C.

Iversen, E.S., and A.W. Moffett. 1962. Estimation of abundance and mortality of a spotted seatrout population. Transactions of the American Fisheries Society 91:395-398.

Iversen, E.S., and D.C. Tabb. 1962. Subpopulations based on growth and tagging studies of spotted seatrout, *Cynoscion nebulosus*, in Florida. Copeia 1962:544-548.

Jaap, W.C. Undated. Stony coral community structure at selected patch reefs, Biscayne National Park, 1977-1981. Unpublished Manuscript. FMRI, St. Petersburg, Florida.

Jaap, W.C. 1984. The ecology of South Florida coral reefs: a community profile. FWS/OBS-82/08. FWS, Washington, DC.

Jaap, W.C. 1988. Statement presented to the U.S. Senate Committee on Appropriations special hearing on bleaching of coral reefs in the Caribbean. Senate Hearing 100-499:55-98.

Jaap, W.C. 1988. The 1987 zooxanthellae expulsion event at Florida reefs. Pages 24-29 (Appendix V) *in* J. Ogden and R. Wicklund, editors. Mass Bleaching of Coral Reefs in the Caribbean: a Research Strategy. National Undersea Research Program Research Report 88-2. NOAA, Washington, D.C.

Jaap, W.C., editor. 1990. Diving for Science...1990. Proceedings of the American Academy of Underwater Sciences Tenth Annual Scientific Diving Symposium. St. Petersburg, Florida.

Jaap, W.C. 1992. Research and monitoring, the Florida reef tract. Testimony presented to the Subcommittee on Environment of the Committee on Space and Technology and the Subcommittee on Oceanography, Great Lakes, and the Outer Continental Shelf of the Committee on Merchant Marine and Fisheries, The U.S. House of Representatives. 23 April 1992, Key Largo, Florida. GPO 102-75:49-53.

Jaap, W.C., J.C. Halas, and R.G. Muller. 1988. Community dynamics of stony corals (Milleporina and Scleractinia) at Key Largo National Marine Sanctuary, Florida, during 1981-1986. Proceedings of the 6th International Coral Reef Symposium 2:237-243.

Jaap, W.C., and P. Hallock. 1990. Coral reefs. Pages 574-616 (Chapter 17) *in* R.L. Myers and J.J. Ewel, editors. Ecosystems of Florida. University of Central Florida Press, Orlando, Florida.

Jaap, W.C., and P. Hallock. 1990. Coral reefs. Pages 97-116 *in* N.W. Phillips and K.S. Larson, editors. Synthesis of Available Biological, Geological, Chemical, Socioeconomic, and Cultural Resource Information for the South Florida Area. Minerals Management Service and CSA, Inc.

Jaap, W.C., W.G. Lyons, P. Dustan, and J.C. Halas. 1989. Stony coral (Scleractinia and Milleporina) community structure at Bird Key Reef, Ft. Jefferson, Dry Tortugas, Florida. Florida Marine Research Publication 46. FMRI, St. Petersburg, Florida.

Jaap, W.C., and F.J. Sargent. In press. The status of the remnant population of *Acropora palmata* (Lamarck 1816) at Dry Tortugas National Park, Florida, with a discussion of possible causes of changes since 1881. Bulletin of Marine Science.

Jaap, W.C., J.L. Wheaton, and K.B. Donnelly. 1990. Materials and methods to establish multipurpose, sustained, ecological research stations on coral reefs at Dry Tortugas. Pages 193-203 *in* W. Jaap, editor. American Academy of Underwater Sciences Tenth Annual Scientific Diving Symposium, St. Petersburg, Florida.

Jaap, W.C., J.L. Wheaton, and K.B. Donnelly. In preparation. A three-year evaluation of community dynamics of coral reefs at Dry Tortugas National Park (formerly Ft. Jefferson National Monument). 36 pp, 23 figures, 15 tables.

Jaap, W.C., J.L. Wheaton, K.B. Donnelly, B.L. Kojis, and J.E. McKenna Jr. 1992. A three-year evaluation of community dynamics of coral reefs at Ft. Jefferson National Monument, Dry Tortugas, Florida, USA. Page 48 *in* R.H. Richmond, editor. Abstracts of the 7th International Coral Reef Symposium, 22-26 June 1992, Guam.

Jaap, W.C., J.L. Wheaton, B.L. Kojis, G.P. Schmahl, D.L. Ballantine, and J. E. McKenna Jr. 1991. Transplanting organisms on a damaged reef at Pulaski Shoal, Ft. Jefferson National Monument, Dry Tortugas, Florida, USA: an experiment to enhance recruitment. Page 34 *in* Reefs Beyond the Golden Gate. Program and Abstracts, 1991 Meeting, International Society for Reef Studies.

Johnson, A.F., and M.G. Barbour. 1990. Dunes and maritime forests. Pages 429-480 (Chapter 13) *in* R.L. Meyers and J.J. Ewel, editors. Ecosystems of Florida. University of Central Florida Press, Orlando, Florida.

Jones, A.C., S.A. Berkeley, J.A. Bohnsack, S.A. Bortone, D.K. Camp, G.H. Darcy, J.C. Davis, K.D. Haddad, M.Y. Hedgepeth, E.W. Irby Jr., W.C. Jaap, F.S. Kennedy Jr., W.G. Lyons, E.L. Nakamura, T.H. Perkins, J.K. Reed, K.A. Steidinger, J.T. Tilmant, and R.O. Williams. 1985. Ocean habitat and fishery resources of Florida. Pages 437-543 *in* W. Seaman Jr., editor. Florida Aquatic Habitat and Fishery Resources. Florida Chapter of American Fisheries Society, Kissimmee, Florida.

Kenworthy, W.J., and D.E. Haunert, editors. 1991. The Light Requirements of Seagrasses. Proceedings of a Workshop to Examine the Capability of Water Quality Criteria, Standards and Monitoring Programs to Protect Seagrasses. NOAA Technical Memorandum NMFS-SEFC-287. NMFS, Beaufort, North Carolina.

Kleppel, G., K. Carter, C. Burkhart and C. Tomas. Submitted. Variations in secondary production on West Florida Shelf. Continental Shelf Research.

Kleppel, G.S., and W. Seaman Jr., editors. 1989. Fishery recruitment in Florida waters: Toward a predictive capability. Report of a workshop held February 15-17, 1989, Live Oak, Florida. Florida Sea Grant Technical Paper No. 57.

Klukas, R.W. 1967. Factors affecting nesting success of loggerhead turtles at Cape Sable, Everglades National Park. File N1415. Report of a modified phase of RSP-7. ENP, Homestead, Florida.

Knight-Jones, P., and T.H. Perkins. In preparation. A revision of *Sabella* and *Bispira* (Sabellidae: Polychaeta). Zoological Journal of the Linnean Society.

Kojis, B.L., K.B. Donnelly, W.C. Jaap, and J.L. Wheaton. 1992. Coral recruitment patterns at Dry Tortugas and Western Sambo reefs, Florida, a SEAKEYS cooperative research project. Proceedings of the Marine Benthic Ecology Meeting (abstract).

Kruer, C.R. 1992. An assessment of Florida's remaining coastal upland natural communities: Florida Keys. FNAI, Tallahassee, Florida.

Kruer, C.R. 1993. Mapping assessment of vessel damage to shallow seagrasses in the Florida Keys. FDNR report, FIO Contract #47-10-123-L3.

Lang, J.C., H.R. Lasker, E.H. Gladfelter, P. Hallock, W.C. Jaap, F.J. Losada, and R. G. Muller. 1992. Spatial and temporal variability during periods of "recovery" after mass bleaching on Western Atlantic coral reefs. American Zoologist 32(6):696-706.

Lang, M.A., and W.C. Jaap, editors. 1989. Diving for Science 1989. Proceedings of the American Academy of Underwater Sciences Ninth Annual Scientific Diving Symposium, Woods Hole, Massachusetts.

Lapointe, B.E., and M. Clarke. In press. Watershed nutrient inputs and coastal eutrophication in the Florida Keys. Estuaries.

Lee, T.N. 1992. Florida Current variability and circulation. Pages 66-130 (Chapter IV) *in* Straits of Florida Physical Oceanography Field Study. Final interpretive report, Volume II. OCS Report MMS 92-0024.

Lee, T.N., K. Leaman, E. Williams, P. Hamilton, T. Berger, and L. Atkinson. 1995. Florida Current meanders and gyre formation in the southern Straits of Florida. Journal of Geophysical Research 100:8607-8620.

Lee, T.N., G. Podesta, E. Williams, J. Splain, and W. Johnson. 1994. Low salinity water in the Straits of Florida. Pages 65-70 *in* M.J. Dowgiallo, editor. Coastal Oceanographic Effects of Summer 1993 Mississippi River Flooding. NOAA Special Report. NOAA Coastal Ocean Office/National Weather Service, Silver Spring, Maryland.

Lee, T.N., and C. Rooth. 1973. Water movements in shallow coastal bays and estuaries. Coastal Zone Management Bulletin No. 3. UM Sea Grant Program (NOAA Sea Grant No. 2-35147).

Lee, T.N., C. Rooth, and E. Williams. 1992. Influence of wind and Florida Current on circulation near the Florida Keys coral reefs. Abstract *in* Physics of Estuaries and Shallow Seas. Proceedings 5th International Biennial Conference on Physics of Estuaries and Coastal Seas. Springer-Verlag.

Lee, T.N., C. Rooth, E. Williams, M.McGowan, A.F. Szmant, and M.E. Clarke. 1992. Influence of Florida Current, gyres and wind-driven circulation on transport of larvae and recruitment in the Florida Keys coral reefs. Continental Shelf Research 12:971-1002.

Lellis, W.A., and M.G. Pardee. 1991. Evaluation of internal tags for postlarval and juvenile spiny lobster, *Panulirus argus*. FDNR Contract C-7037.

Livingston, R.J. 1982. Trophic organization of fishes in a coastal seagrass system. Marine Ecology Progress Series 7:1-12.

Livingston, R.J. 1990. Inshore marine habitats. Pages 549-573 (Chapter 16) *in* R.L. Meyers and J.J. Ewel, editors. Ecosystems of Florida. University of Central Florida Press, Orlando, Florida.

Loope, L., M. Duever, A. Herndon, J. Snyder, and D. Jansen. 1994. Hurricane impact on uplands and freshwater swamp forest. BioScience 44(4):238-246.

Lynch, M.P., B.L. Laird, N.B. Theberge, and J.C. Jones. 1976. An assessment of estuarine and nearshore marine environments. OBS/FWS-76/05. FWS, Washington, D.C.

Lynts, G.W. 1966. Relationship of sediment-size distribution to ecologic factors in Buttonwood Sound, Florida Bay. Journal of Sedimentary Petrology 36(1):66-74.

Lyons, W.G. 1988. A review of Caribbean Acanthochitonidae (Mollusca: Polyplacophora) with descriptions of six new species of *Acanthochitona* Gray, 1821. American Malacological Bulletin 6(1):79-114.

Marelli, D.C., and W.C. Jaap. 1990. Description of a low-cost, shallow-water, surface-supplied diving system. Pages 267-271 *in* W. Jaap, editor. American Academy of Underwater Sciences Tenth Annual Scientific Diving Symposium, St. Petersburg, Florida.

Marelli, D.C., M.K. Krause, W.S. Arnold, and W.G. Lyons. In press. Systematic relationships among Florida populations of *Argopecten irradians* sensu lato (Lamarck, 1819) (Bivalvia: Pectinidae). Nautilus.

Marszalek, D.S. Undated. Florida reef tract marine habitats and ecosystems. 10 maps. RSMAS, Miami, Florida.

Matthews, T.R., and P. Donovon-Potts. 1993. An evaluation of mooring buoys in the Florida Keys National Marine Sanctuary. FDNR Contract C-8013.

Matthews, T.R., J.H. Hunt, and D.W. Heatwole. Submitted. A comparison of morphometric relationships between Florida and Caribbean populations of the spiny lobster, *Panulirus argus*. Publication of the FMRI, St. Petersburg, Florida.

Maul, G.A., and D.M. Martin. 1993. Sea level rise at Key West, Florida, 1846-1992: America's longest instrument record? Geophysical Research Letters 20(18):1955-1958.

McCoy, E.D. 1981. Rare, threatened, and endangered plant species of southwest Florida and potential OCS activity impacts. FWS/OBS-81/50. FWS, Washington, D.C.

McGowan, M.F. 1991. The Pourtales Gyre affects distribution and recruitment of reef fish larvae and lobster phyllosomata to the Florida Keys. Proceedings of the Association of Island Marine Laboratories of the Caribbean (1991)24 (abstract).

McGowan, M.F. 1992. Annex IV: IOCARIBE-TRODERP-CODERP (COral Reef DEmersal Recruitment Project). Pages 16-17 *in* B.E. Brown, W.A. Erb, and G.A. Maul. Intra-Americas Sea Marine Science Meeting of U.S. Experts: Report of a Workshop Held in Miami, Florida, December 17-19, 1990. NOAA Technical Memorandum NMFS-SEFSC-308. NMFS, Miami, Florida.

McGowan, M.F., F. Al-Yamani, and T.R. Capo. 1991. Taxonomic composition and abundance of Biscayne Bay zooplankton in March, May, and August 1990. Technical Report RSMAS TR-91-002. RSMAS, Miami, Florida.

McGowan, M.F., S.S. Cha, W.J. Richards. In press. Effects of coastal oceanography on fish larvae assemblages in the Florida Keys. Continental Shelf Research.

McGowan, M.F., and M. Harrington. 1992. Juvenile fish collected from puerulus settlement traps in the Florida Keys. SEFCAR unprocessed data report 28 April 1992. 15p.

McGowan, M.F., and J.P. Umaran. Submitted. Seasonal occurrence and horizontal and vertical distribution of leptocephali of tarpon, bonefish, and ladyfish off the Florida Keys in 1989-1990. Copeia.

McGowan, M.F., and C. Yeung. 1990. Interspecific differences in lobster recruitment to the Florida Keys based on larval transport. Abstract. The Western Society of Naturalists 71st Annual Meeting.

McGowan, M.F., C. Yeung, and W.J. Richards. Submitted. Florida's spiny lobsters, *Panulirus argus*, recruit from the Caribbean: evidence from oceanographic transport and distribution of larvae. Journal of Fisheries Oceanography.

McIvor, C.C., J.A. Ley, and R.D. Bjork. 1994. Changes in freshwater inflow from the Everglades to Florida Bay including effects on biota and biotic processes: a review. Pages 117-146 *in* S.M. Davis and J.C. Ogden, editors. Everglades: The Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Florida.

Meeder, J.F., and R.E. Turner, organizers. 1994. The Second Coastal Wetland Ecology and Management Symposium: Sustained Wetland Productivity through Scientific Research, December 6-8, 1994, Key Largo, Florida. Program with abstracts. FIU, LSU, NBS, NMFS, and Remote Data Systems, Inc.

Moffler, M.D., and M.J. Durako. 1987. Reproductive biology of the tropical-subtropical seagrasses of the southeastern United States. Pages 77-88 *in* M.J. Durako, R.C. Phillips, and R.R. Lewis, editors. Proceedings of the Symposium on Subtropical-Tropical Seagrasses of the Southeastern United States. Florida Marine Research Publication No. 42. FMRI, St. Petersburg, Florida.

Mooers, C., coordinator. 1992. Virginia Key Coastal Ocean Sciences Symposium, 20 March 1992. Division of Applied Marine Physics, RSMAS, Miami, Florida.

Mooers, C.N.K., convener. 1994. Florida Coastal Ocean Sciences Symposium, 21 and 22 April 1994. Ocean Pollution Research Center, RSMAS, Miami, Florida.

Murphy, T.H. 1984. Aerial and ground surveys of marine turtle nesting beaches in the Southeast Region, U.S. Final report to NMFS, Contract Number NA83-GA-C-00021. NMFS, Miami, Florida.

National Oceanic and Atmospheric Administration. 1994. Florida Keys National Marine Sanctuary, Draft Environmental Impact Statement/Management Plan. Volumes I, II, and III. Sanctuaries and Reserves Division, NOAA, Washington, D.C.

National Oceanic and Atmospheric Administration. 1995. NOAA Florida Bay Program, 1995 implementation Plan. NOAA, Washington, D.C.

Norris, M., and J. Wheaton. 1991. Synopsis of live rock landings and historical review of issues. Florida Marine Fisheries Commission meeting, Miami, Florida, December 6, 1991. Florida Marine Fisheries Commission, Tallahassee, Florida.

Odum, W.E., and C.C. McIvor. 1990. Mangroves. Pages 517-548 (Chapter 15) *in* R.L. Meyers and J.J. Ewel, editors. Ecosystems of Florida. University of Central Florida Press, Orlando, Florida.

Odum, W.E., C.C. McIvor, and T.J. Smith III. 1982. The ecology of mangroves of south Florida: a community profile. FWS/OBS-81/24. FWS, Washington, D.C.

Ogden, J.C., W.B. Robertson, G.E. Davis, and T.W. Schmidt. 1974 (revised). Pesticides, polychlorinated biphenyls and heavy metals in upper food chain levels, Everglades National Park and vicinity. South Florida Environmental Project: Report D1-SFEP-74-16. ENP, Homestead, Florida.

Orth, R.J., and K.L. Heck. 1980. Structural components of eelgrass (*Zostera marina*) meadows in lower Chesapeake Bay fishes. Estuaries 3:278-288.

Ortner, P.B., D.E. Hoss, and J.A. Browder, editors. 1993. NOAA Workshop on the Restoration of Florida Bay, Miami, July 14-16, 1993. NMFS, Miami, Florida.

Parrish, J.D. 1989. Fish communities of interacting shallow-water habitats in tropical oceanic regions. Marine Ecology Progress Series 58:143-160.

Paul, R.T. 1977. Banding studies of the white-crowned pigeon in Florida and the Bahamas. Pages 25-31 *in* Proceedings of the International White-Crowned Pigeon Conference, Nassau, Bahamas, 11 November 1976. Bahamas National Trust, Nassau, Bahamas.

Perkins, T.H., W.G. Lyons, J.H. Hunt, and P. McVety (principal authors). 1991. Marine resource issues and research in the Florida Keys. Division of Marine Resources, FDNR. March 1991 (Revised May 1991).

Peters, E.C., S.D. Cairns, M.E.Q. Pilsom, J.W. Wells, W.C. Jaap, J.C. Lang, C.E. (Cummings) Vasleski, and L. St. Pierre Gollahon. 1988. Nomenclature and biology of *Astrangia poculata (= A. danae, = A. astreiformis)* (Cnidaria: Anthozoa). Proceedings of the Biological Society of Washington 101(2):234-250.

Petersen, M.E., T.H. Perkins, and J.M. Orensanz. In preparation. A contribution to the systematics of the lesser Chrysopetalidae (Polychaeta).

Pike, C.S. 1993. A population dynamic study of the South Florida spiny lobster (*Panulirus argus*) fishery using simulation modelling. Ph.D. dissertation. UM, Coral Gables, Florida.

Pikula, L., and S. Elswick, compilers. 1992. Ecosystems of the Florida Keys, a bibliography. Library and Information Services Division Current References 92-1. National Oceanographic Data Center, NOAA. NOAA Central Library, Rockville, Maryland.

Pimm, S.L., G.E. Davis, L. Loope, C.T. Roman, T.J. Smith III, and J.T. Tilmant. 1994. Hurricane Andrew. BioScience 44(4):224-229.

Planning Department Staff, SFWMD. 1992. Dade County-Florida Keys water supply background document. Draft report and appendices. Planning Department, SFWMD, West Palm Beach, Florida.

Pollard, D.A. 1984. A review of ecological studies on seagrass-fish communities, with particular reference to recent studies in Australia. Aquatic Botany 18:3-42.

Porter, J.M., and O.W. Meier. 1992. Quantification of loss and change in Floridian reef coral populations. American Zoologist 32:625-640.

Powell, A.B., D.E. Hoss, W.F. Hettler, D.S. Peters, L. Simoneaux, and S. Wagner. 1987. Abundance and distribution of ichthyoplankton in Florida Bay and adjacent waters. Report SFRC-87/01. SFRC, ENP, Homestead, Florida.

Preisendorfer, R.W. 1988. Principal components analysis in meteorology and oceanography. *In* C.D. Mobley, editor. Developments in Atmospheric Science 17. Elsevier.

Quinn, J.F. Jr. 1992. The importance of sponges in Florida ecosystems. Unpublished report to Florida Marine Fisheries Commission. FMRI, St. Petersburg, Florida.

Quinn, J.F. Jr. In preparation. The Trochidae of the Gulf of Mexico (Prosobranchia: Archaeogastropoda). Memoirs of the Hourglass Cruises.

Richards, W.J., and J.A. Bohnsack. 1982. The conflicts and controversies surrounding the use of reef fish resources. Marine Recreational Fisheries 7:45-56.

Robblee, M.B., T.A. Armentano, and R.W. Snow. 1993. A research program for restoration of Florida Bay. Draft. SFRC, ENP, Homestead, Florida.

Robblee, M.B., T.R. Barber, P.R. Carlson, M.J. Durako, J.W. Fourqurean, L.K. Muehlstein, D. Porter, L.A. Yarbro, R.T. Zieman, and J.C. Zieman. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). Marine Ecology Progress Series 71:297-299.

Roemig, R., M.E. Clarke, and D. Olson. Submitted. Comparison of reaction distances of larval snapper and hamlets to a moving stimulus and relation to predation vulnerability. J. Phys. Oceanogr.

Roman, C.T., N.G. Aumen, J.C. Trexler, R.J. Fennema, W.F. Loftus, and M.A. Soukup. 1994. Hurricane Andrew's impact on freshwater resources. BioScience 44(4):247-255.

Rooth, C., and L. Xie. 1992. Air-sea boundary layer dynamics in the presence of mesoscale surface currents. Journal of Geophysical Research-Oceans 97:4431-4438.

Rooth, C., and L. Xie. Submitted. The equivalent mountain ridge induced by an oceanic jet. Tellus.

Rooth, C.G., L. Xie, and T.N. Lee. Submitted. Effect of wind direction on the surface transport patterns and upwelling distribution in a coastal eddy. J. Phys. Oceanogr.

Ross, M.S., J.J. O'Brien, and L.d.S.L. Sternberg. 1994. Sea level rise and the reduction in pine forests in the Florida Keys. Ecological Applications 4(1):144-156.

Rothschild, B.J., and J.S. Ault. 1994. Population-dynamic patch structure. Journal of Plankton Research

Rutherford, E.S. 1982. Age, growth and mortality of spotted seatrout. M.S. thesis. UM, Coral Gables, Florida.

Sale, P.F., editor. 1991. The ecology of fishes on coral reefs. Academic Press, Inc., San Diego.

Schirripa, M.J. 1992. Simulation modeling and conservation standards for spotted seatrout (*Cynoscion nebulosus*) in Everglades National Park. M.S. thesis, FIU, Miami, Florida.

Schirripa, M.J., K. Burns, and J.A. Bohnsack. 1993. Reef fish release survival based on tag and recovery data. A report to the Gulf of Mexico Fishery Management Council. Miami Laboratory Contribution No. MIA-92/93-34. NMFS, Miami, Florida.

Schirripa, M.J., and C.P. Goodyear. 1994. Simulation modeling of conservation standards for spotted seatrout (*Cynoscion nebulosus*) in Everglades National Park. Bulletin of Marine Science 54(3):1019-1035.

Schmidt, T.W. 1991. Scientific studies in the coastal and estuarine areas of Everglades National Park: an annotated bibliography. Research/Resources Management Report SER-91/02. NPS, Southeast Regional Office, Atlanta, Georgia.

Schomer, N.S., and R.D. Drew. 1992. An ecological characterization of the Lower Everglades, Florida Bay and the Florida Keys. FWS/OBS-82/58.1. FWS, Washington, D.C.

Schroeder, B.A., and A.M. Foley. 1995. Population studies of marine turtles in Florida Bay. Page 17 (abstract) *in* J.I. Richardson and T.H. Richardson, compilers. Proceedings of the Twelfth Annual Symposium on Marine Turtle Biology and Conservation, 1992. NOAA Technical Memorandum NMFS-SEFSC-361. NMFS, Miami, Florida.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Scott, G.I., D.S. Baughman, A.H. Trim, and J.C. Dee. 1987. Lethal and sublethal effects of insecticides commonly found in nonpoint source agricultural runoff to estuarine fish and shellfish. Pages 251-173 *in* W.B. Vernberg, A. Calabrese, F.P. Thurberg, and F.J. Vernberg, editors. Pollution Physiology of Estuarine Organisms. University of South Carolina Press, Columbia, SC.

Scott, G.I., M.H. Fulton, M.C. Crosby, P.B. Key, J.W. Daugomah, J.T. Waldren, E.D. Strozier, C.J. Louden, G.T. Chandler, T.F. Bidleman, K.L. Jackson, T.W. Hampton, T. Huffman, A. Shulz, and M. Bradford. 1994. Agricultural insecticide runoff effects on estuarine organisms: correlating laboratory and field toxicity tests, ecophysiology bioassays, and ecotoxicological biomonitoring. EPA Environmental Research Laboratory, Gulf Breeze, Florida.

Scott, G.I., M.H. Fulton, J.W. Daugomah, E.D. Strozier, P.B. Key, P.L. Pennington, B.C. Thompson, E.F. Wirth, and G. Thayer. 1994. Monitoring of pesticides in surface waters of Florida Bay and adjacent

agricultural watersheds: implications for future management of freshwater inputs into Florida Bay. Interim report. NMFS, Charleston, South Carolina.

Scott, G.I., M.H. Fulton, P.B. Key, E.F. Wirth, G. Thayer, and G.T. Chandler. 1995. Monitoring of pesticides and other chemical contaminants in surface waters, sediments and biota of Florida Bay and adjacent terrestrial watersheds: an ecotoxicological assessment of endosulfan and other contaminants which are potential endocrine hormone mimics on estuarine and benthic organisms. Proposal to NOAA Florida Bay Program. NMFS, Charleston, South Carolina.

Scott, G.I., D.W. Moore, M.H. Fulton, T.W. Hampton, J.M. Marcus, G.T. Chandler, K.L. Jackson, D.S. Baughman, A.H. Trimm, C.J. Loudan, and E.R. Patterson. 1989. Agricultural insecticide runoff effects on estuarine organisms: correlating laboratory and field toxicity testing with ecotoxicological biomonitoring. Vol. I and II, and Annual Report. EPA Environmental Research Laboratory, Gulf Breeze, Florida.

Serafy, J.E., and R.M. Harrel. 1993. Behavioral response of fishes to increasing pH and dissolved oxygen: field and laboratory observations. Freshwater Biology 30:53-61.

Sheridan, P.F. 1992. Comparative habitat utilization by estuarine macrofauna within the mangrove ecosystem of Rookery Bay, Florida. Bulletin of Marine Science 50(1):21-39.

Silberman, J.D. 1993. Molecular variation in the spiny lobster *Panulirus argus*: recruitment aspects. Ph.D. dissertation. UM, Coral Gables, Florida.

Skinner, R.H., and E.F. Corcoran. 1989. John Pennekamp Coral Reef State Park assessment of water quality data from five stations. Volume I: November 1982 - December 1984. FDNR.

Skinner, R.H., and W. Jaap. 1986. Trace metals and pesticides in sediment and organisms in John Pennekamp Coral Reef State Park. Final report, Coastal Zone Grant 1984-1985 (Processed). FDNR.

Smith, T.J. III. 1993. An environmental characterization of the Rookery Bay National Estuarine Research Reserve: phase I. Final report, Grant NA17OR0326-01, to Sanctuaries and Reserves Division, Office of Ocean and Coastal Resource Management, NOAA. FDEP, Naples, Florida.

Smith, J.T. III, M.B. Robblee, H.R. Wanless, and T.W. Doyle. 1994. Mangroves, hurricanes, and lightning strikes. BioScience 44(4):256-262.

Smith-Vaniz, W.F., J.A. Bohnsack, and J.D. Williams. 1995. Reef fishes of the Florida Keys. Pages 279-284 *in* Our Living Resources. DOI, NBS, Washington, D.C.

Snedaker, S.C., and A.E. Lugo. 1973. The role of mangrove ecosystems in the maintenance of environmental quality and a high productivity of desirable fisheries. Final report to Bureau of Sport Fisheries and Wildlife, Contract No. 14-16-008-606. Center for Aquatic Sciences, UF, Gainesville, Florida.

South Florida Water Management District. 1994. Everglades Forever Act. Ecosystem Update, May 1994. SFWMD, West Palm Beach, Florida.

Stevely, J.M., D.E. Sweat, and S.D. Brown. 1993. Annual synopsis and final report, Florida Keys sponge survey project. Unpublished report to Florida Sea Grant, Gainesville, Florida.

Stewart, K.W. 1961. Contributions to the biology of the spotted seatrout (*Cynoscion nebulosus*) in the Everglades National Park. Master's thesis. UM, Coral Gables, Florida.

Stoner, A.W. 1983. Distribution of fishes on seagrass meadows: role of macrophyte biomass and species composition. Fishery Bulletin 81:837-846.

Strom, R.N, R.S. Braman, W.C. Jaap, P. Dolan, K.B. Donnelly, and D.F. Martin. 1992. Analysis of selected trace metals and pesticides offshore of the Florida Keys. Florida Scientist 55(1):1-13.

Sutherland, D.L., and J.A. Bohnsack. 1987. An interim report: the relationship of reef fish size and species composition to mesh sizes of wire fish traps. A report for the Gulf of Mexico Fishery Management Council. CRD-86/87-27.

Sutherland, D.L., J.A. Bohnsack, D.E. Harper, C.M. Holt, M.W. Hulsbeck, and D.B. McClellan. 1991. Preliminary report: reef fish size and species selectivity by wire fish traps in southern Florida waters. Proceedings of the Gulf and Caribbean Fisheries Institute 40(1989):108-125.

Tabb, D.C. 1956. Contributions to the life history of the spotted weakfish, *Cynoscion nebulosus*, of the Florida East Coast. Master's thesis. UM, Coral Gables, Florida.

Tabb, D.C. 1963. A summary of existing information on the fresh-water, brackish-water and marine ecology of the Florida Everglades region in relation to fresh-water needs of Everglades National Park. Report submitted to the Office of the Superintendent, ENP and Fort Jefferson National Monument. Institute of Marine Science, UM.

Tabb, D.C., D.L. Dubrow, and A.E. Jones. 1962. Studies on the biology of the pink shrimp, *Penaeus duorarum* Burkenroad, in Everglades National Park, Florida. State of Florida Board of Conservation Technical Series No. 37.

Tabb, D.C., D.L. Dubrow, and R.B. Manning. 1962. The ecology of northern Florida Bay and adjacent estuaries. State of Florida Board of Conservation Technical Series No. 39.

Tabb, D.C., and A.C. Jones. 1962. Effect of Hurricane Donna on the aquatic fauna of north Florida Bay. Transactions of the American Fisheries Society 91(4):375-378.

Tabb, D.C., and R.B. Manning. 1961. A checklist of the flora and fauna of northern Florida Bay and adjacent brackish waters of the Florida mainland collected during the period July, 1957 through September, 1960. Bulletin of Marine Science of the Gulf and Caribbean 11(4):552-649.

Ten Hove, H.A., and T.H. Perkins. In preparation. New and little known species of the genus *Hydroides*. Serpulidae (Polychaeta) from the Caribbean: V. Natural History of the Caribbean Region.

Te Strake, D., W.C. Japp, E. Truby, and R. Reese. 1988. Fungal filaments in *Millepora complanata* Lamarck, 1816 (Cnidaria: Hydrozoa) after mass expulsion of zooxanthellae. Florida Scientist 51(3/4):184-188.

Thayer, G.W., D.R. Colby, and W.F. Hettler Jr. 1987. Utilization of the red mangrove prop root habitat by fishes in south Florida. Marine Ecology Progress Series 35:25-28.

Thayer, G.W., W.F. Hettler Jr., A.J. Chester, D.R. Colby, and P.J. McElhaney. 1987. Distribution and abundance of fish communities among selected estuarine and marine habitats in Everglades National Park. Report SFRC-87/02. SFRC, ENP, Homestead, Florida.

Thayer, G.W., M.W. LaCroix, and P.L. Murphey. 1993. Response of fisheries communities in western Florida Bay to the die off of seagrass. II. Basin habitats. Pages 123-124 *in* The Science and Management of Coastal Estuarine Systems. 12th Biennial International Estuarine Research Federation Conference (Abstracts).

Thomas, L.P., compiler. 1975. Shallow-Water Marine Environments of the Caribbean. A collection of reports done by students in MBS 675. RSMAS, Miami, Florida.

Tilmant, J.T., R.W. Curry, R. Jones, A. Szmant, J.C. Zieman, M. Flora, M.B. Robblee, D. Smith, R.W. Snow, and H. Wanless. 1994. Hurricane Andrew's effects on marine resources. BioScience 44(4):230-237.

Tilmant, J.T., W.C. Jaap, J.L. Wheaton, and W. Hudson. 1989. M/V *Mavro Vetranic* grounding, Pulaski Shoal Reef - Ft. Jefferson National Monument: environmental impact assessment. Unpublished report. NPS.

Tomas, C.R. 1994. Influence of Mississippi River water on the west Florida Shelf. Pages 60-64 *in* M.J. Dowgiallo, editor. Coastal Oceanographic Effects of Summer 1993 Mississippi River Flooding. NOAA Special Report. NOAA Coastal Ocean Office/National Weather Service, Silver Spring, Maryland.

Tomas, C. 1995. Coastal production and sportfish plankton dynamics on the West Florida Shelf. Final report to FWS. FMRI, St. Petersburg, Florida.

Tomas, C., and D. Baden. 1993. Determination and distribution of low level populations of *Gymnodinium breve* as measured by a sensitive ELISA technique. 6th International Conference on Toxic Marine Phytoplankton (abstract).

U.S. Fish and Wildlife Service/Florida Department of Natural Resources. 1992. Management agreement for backcountry portions of Key West National Wildlife Refuge, Great White Heron National Wildlife Refuge, and National Key Deer Refuge. FWS, Atlanta, Georgia, and FDNR, Tallahassee, Florida.

VanArman, J., J. Muliken, D. Swift, S. Bellmund, L. Gulick, L. Bos, and S. Formati. 1989. Draft Surface Water Improvement and Management Plan for the Everglades. SFWMD, West Palm Beach, Florida.

Weiner, A.H. Undated. The hardwood hammocks of the Florida Keys: an ecological study. The NAS and the Florida Keys Land Trust.

Weinstein, M.P., and K.L. Heck. 1979. Ichthyofauna of seagrass meadows along the Caribbean coast of Panama and in the Gulf of Mexico: composition, structure and community ecology. Marine Biology 50:97-107.

Weinstein, M. P., and R.W. Yerger. 1976. Electrophoretic investigation of subpopulations of the spotted seatrout, *Cynoscion nebulosus* (Curvier), in the Gulf of Mexico and Atlantic Coast of Florida. Comparative Biochemistry and Physiology 54B:97-102.

Weisberg, R.H. 1994. Transport of Mississippi River water to the west Florida Shelf. Pages 55-59 *in* M.J. Dowgiallo, editor. Coastal Oceanographic Effects of Summer 1993 Mississippi River Flooding. NOAA Special Report. NOAA Coastal Ocean Office/National Weather Service, Silver Spring, Maryland.

Wheaton, J.L. 1989. The marine-life fishery for "live rock": biological and ecological assessment of the product and implications for harvest. Unpublished report. FMRI, St. Petersburg, Florida.

Wheaton, J.L., and W.C. Jaap. 1988. Corals and other prominent benthic Cnidaria of Looe Key National Marine Sanctuary, Florida, USA. Florida Marine Research Publication 43. FMRI, St. Petersburg, Florida.

White, M.W., J.W. Porter, J.A. Bohnsack, and J.A. Rivera. 1985. Baseline measurements of spatial arrangements and population dynamics in marine sanctuary communities. Final report to Sanctuary Programs Division, Office of Ocean and Coastal Resource Management, NOAA.

Wiemeyer, S.N., T.G. Lamont, and L.N. Locke. 1980. Residues of environmental pollutants and necropsy data for eastern United States ospreys, 1964-1973. Estuaries 3(3):155-167.

Williams, C.D., D.M. Nelson, L.C. Clements, M.E. Monaco, S.L. Stone, L.R. Settle, C. Iancu, and E.A. Irlandi. 1990. Distribution and abundance of fishes and invertebrates in eastern Gulf of Mexico estuaries. ELMR Report No. 6. Strategic Assessment Branch, NOS/NOAA, Rockville, Maryland.

Williams, E. and T.N. Lee. SEFCAR current meter data reports. Technical reports over the period April 1989 to May 1993. RSMAS, Miami, Florida.

Williams, E., and T. N. Lee. SEFCAR hydrographic data report for the period May 1989 to May 1991. Technical report. RSMAS, Miami, Florida.

Wood, D.A. 1994. Official lists of endangered and potentially endangered fauna and flora in Florida. FGFWFC, Tallahassee, Florida.

Xie, L. 1992. The effect of current-induced stress perturbation on large- and meso-scale air-sea interactions. Ph.D. dissertation. UM, Coral Gables, Florida.

Yeung, C. 1991. The vertical, horizontal, and seasonal distribution and abundance of palinurid and scyllarid lobster phyllosoma larvae in the Florida Keys in relation to the circulation, May 1989-February 1990. Master's thesis. UM, Coral Gables, Florida.

Yeung, C., and M.F. McGowan. 1991. Differences in inshore-offshore and vertical distribution of Phyllosoma larvae of *Panulirus*, *Scyllarus*, and *Scyllarides* in the Florida Keys in May-June, 1989. Bulletin of Marine Science 49(3):699-714.

Yoshioka, H., T.N. Lee, M. McGowan, and G. Paffenhofer. Undated. Comparison of acoustic Doppler current profiles derived backscatter with plankton abundance in SEFCAR and SABRE study regions. Draft Technical Report. RSMAS, Miami, Florida.

Zieman, J.C. 1970. The effects of a thermal effluent stress on the seagrasses and macroalgae in the vicinity of Turkey Point, Biscayne Bay, Florida. Ph.D. dissertation. UM, Coral Gables, Florida.

Zieman, J.C. 1982. The ecology of the seagrasses of South Florida: a community profile. FWS/OBS-82/25. FWS, Washington, D.C.

Zieman, J.C., S.A. Macko, and A.L. Mills. 1984. Role of seagrasses and mangroves in estuarine food webs: temporal and spatial changes in stable isotope composition and amino acid content during decomposition. Bulletin of Marine Science 35(3):380-392.

Zieman, J.C., and R.T. Zieman. 1989. The ecology of seagrass meadows of the west coast of Florida: a community profile. Biological Report 85(7.25). FWS, Washington, D.C.

FLORIDA BAY SCIENCE PLAN

A science planning document provided to the Interagency Working Group on Florida Bay

April 1994

Drafting Committee:

National Park Service:
Thomas V. Armentano
Everglades National Park/South Florida Natural Resources Center

National Biological Survey:
Michael Robblee
South Florida/Caribbean Field Unit

National Oceanic and Atmospheric Administration:
Peter Ortner
Atlantic Oceanic and Meteorological Laboratory

Nancy Thompson
Southeast Fisheries Science Center

South Florida Water Management District:
David Rudnick

Florida Department of Environmental Protection:
John Hunt
Florida Marine Research Institute

I. EXECUTIVE SUMMARY

The following science plan was developed by the Florida Bay Interagency Working Group, which was initiated by Everglades National Park in January 1993. The plan focuses upon the research, monitoring, and modeling objectives that must be addressed to guide the restoration of Florida Bay and represents a synthesis of research plans prepared over the past year by several federal and state agencies. With additional plans focused on the coastal mangrove estuaries of southwest Florida, the Florida Reef Tract, and, the Florida Keys and Dry Tortugas, this science plan will serve as the basis for restoration of Sub-region 8 under the aegis of the South Florida Ecosystem Task Force.

Administratively, an interagency research plan for Florida Bay is especially needed because of the number of agencies that have jurisdiction over areas affected by Florida Bay research and restoration. Representatives of the major agencies (Department of Commerce, Department of Interior, FDEP, and the South Florida Water Management District) have participated in drafting an interagency plan consistent with their respective responsibilities. As recommended by a disinterested advisory panel convened in September 1993 at the behest of the Assistant Secretary of the Interior for Fish and Wildlife and Parks, a management framework has been explicitly set forth to ensure continuing integration of the activities of the different agencies. This framework includes an Interagency Program Management Committee, a Review Panel, and a Technical Advisory Group. It was agreed that individual implementation plans prepared by each agency should not only be consistent with the scientific approach and priorities of the interagency science plan but each should also include the following:

1) Cross-references to and discussions of the implementation plans developed by other agencies,
2) A funding source for participation in annual interagency principal investigator meetings at which data and results can be exchanged, and
3) Compatible data-management plans and procedures.

The management objective for Florida Bay is to restore it to a naturally functioning ecosystem. Elements of the restoration process and the degree to which management can effect change, in large part, define the focus, approach, and priorities of this science plan. To support restoration, the science program must be long-term and goal-oriented in perspective. The program must be committed to the process of integrating scientific understanding of Florida Bay into the management decision-making process and must focus on interdisciplinary ecosystem-based research. The specific objectives of the science program should include the following:

1) Developing an understanding of the condition of Florida Bay prior to significant alteration by man;
2) Separating anthropogenically induced changes in Florida Bay from natural system variation:
3) Developing a basic understanding of the ecology of Florida Bay by evaluating alternative hypotheses;
4) Developing the capability to predict how the ecosystem as a whole and how a suite of species that collectively may be considered indicators of Florida Bay ecosystem health respond to perturbation.

The approach recommended embraces a closely linked program of monitoring, research, and modeling. By monitoring, we can track critical ecosystem parameters and provide baseline data and model parameterization. By conducting research, we can develop an understanding of the physical and biological processes regulating Bay ecosystem status, test model predictions, and evaluate cause and effect relationships. Computer simulation models, in which our best understanding of the Bay's ecology within the regional landscape is expressed, will be used in a predictive mode to assess system response to change, to hindcast historical conditions, and to develop and select management alternatives.

Four general topic areas were considered: 1) water budgets, circulation dynamics, and salinity; 2) water quality and nutrient cycling; 3) seagrass, mangrove, and hardbottom habitats; and 4) living resources. Following the recommendation of the advisory panel, priorities were then established within each of the general topic areas by formulating questions that must be answered in order to understand the ecosystem of Florida Bay, the changes it has undergone, and the possible effects of alternative restoration scenarios. These are some of the questions posed:

1. What is the relationship of surface water and groundwater flows through the Everglades to the salinity of Florida Bay?

2. What has been the effect of the relative lack of storms over the past three decades on the buildup of sediments, nutrients, and organic material in the Bay?

3. What have been the effects in Florida Bay of increased residence time of water caused by restricted water flow through channels between the Keys, shoaling, and reduced freshwater inflows?

4. What are the sources, quantities, and ecological effects of "external" nutrients introduced into Florida Bay?

5. What are the rates of nutrient exchange between the sediment and water column within Florida Bay, and what controls the magnitude and direction of these fluxes?

6. What are the rates of nutrient assimilation by phytoplankton in the Bay, and what limits the growth of the phytoplankton assemblage?

7. What are the sources, quantities, and effects of toxic pollutants introduced into the Florida Bay ecosystem?

8. What is the cause of turbidity in the Bay, and what is its effect on Bay water quality?

9. What environmental and biological factors explain the observed distribution of seagrasses within the Bay and the recent die-off?

10. What environmental factors explain the pattern of mangrove die-back within the Florida Bay ecosystem?

11. What has been the cause and consequence of sponge die-off and the subsequent alteration of hardbottom communities?

12. Has recruitment into Florida Bay been affected by habitat changes in Florida Bay, and have altered environmental conditions affected growth and survival of animals in Florida Bay?

13. Has habitat degradation or loss caused a reduction in fishery productivity in the Bay?

14. Have environmental and habitat changes in the Bay affected the distribution and reproductive success of higher-trophic-level consumers?

II. INTRODUCTION AND FRAMEWORK

A. Context

Since 1987, a series of changes in Florida Bay (Fig. 1) have become evident to even the most casual observer. To date, these have included extensive losses of seagrass habitat, diminished water clarity, micro-algal blooms of increasing intensity and duration, and population reductions in economically significant species such as pink shrimp, sponges, lobster, and recreational gamefish. In response to heightened local concern, the representatives of a number of state and federal agencies began meeting in January 1993 as an informal Working Group for Florida Bay. In fact, however, not only Florida Bay but the entire South Florida ecosystem, a unique, interdependent landscape-seascape, may be threatened. With national attention to this crisis, the relevant federal agencies (see below) entered into an historic Agreement[1] to cooperate and work with the State of Florida "to address and solve the myriad issues involved in restoring and maintaining the unique world resources embodied in the South Florida ecosystem."

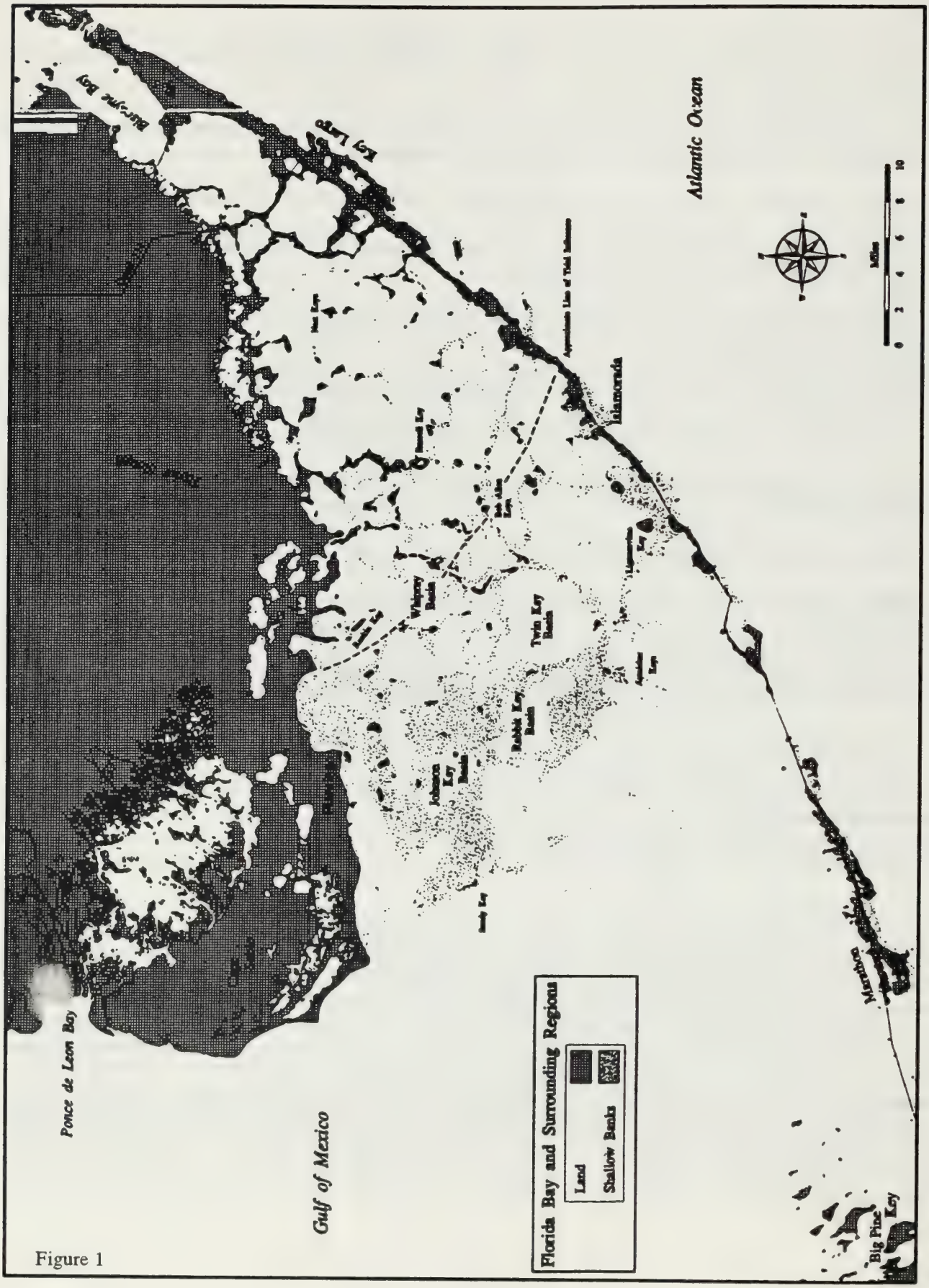

Florida Bay and Surrounding Regions
Land
Shallow Banks
Gulf of Mexico
Ponce de Leon Bay
Atlantic Ocean
Big Pine Key
Miles

Figure 1

The Agreement established an interagency Task Force consisting of Departmental Assistant Secretaries (or their equivalents) from the Dept. of the Interior (DOI), the Dept. of Commerce (DOC), Dept. of the Army (Civil Works), Dept. of Justice, Dept. of Agriculture, and the Environmental Protection Agency. It is intended that, as soon as possible, the appropriate State of Florida (Department of Environmental Protection/DEP) and regional (South Florida Water Management District/SFWMD) agencies will be invited to become members of the Task Force and its subsidiary bodies. The Task Force has already established a South Florida Management and Coordination Working Group consisting of local administrators, which has in turn established, among other advisory subgroups, a Scientific Working Sub-Group to provide necessary technical advice. This last body began to meet in October 1993, and, at the request of the Army Corps, has provided the South Florida Management and Coordination Working Group (and Task Force) with a set of objectives and success criteria for the hydrological and ecological restoration of the South Florida Ecosystem. Objectives and criteria were separately provided for ten subregions, which were viewed not as a set of isolated geographic areas but rather as an integrated whole[2].

For each subregion (or combinations thereof), detailed science plan have been developed that will be integrated into a regional, ecosystem-based science program. The Agreement not only envisions such integration, but also explicitly sanctions line agency cooperation and facilitates mechanisms (e.g., interagency transfers of funds) needed to accomplish efficient integration.

The document to follow was developed at the request of the chairman of the South Florida Management and Coordination Working Group for Florida Bay, the Superintendent of Everglades Park. It represents the first interagency science plan for any South Florida subregion since the Agreement was executed.

The following plan focuses upon the research, monitoring, and modeling objectives that must be addressed in the restoration of Florida Bay. The substance of this plan is a synthesis of the following: a draft research program for Florida Bay developed by the National Park Service's South Florida Research Center (now the South Florida Natural Resources Center)[3]; a draft report from a NOAA workshop held to define Florida Bay research priorities[4]; and the internal draft research plans recently prepared by the South Florida Water Management District, the Florida Department of Environmental Protection, and the United States Geological Survey. The synthesis effort was preceded by a scientific review of Florida Bay problems conducted by a panel of nationally recognized scientists, as requested by Assistant Secretary Frampton (DOI)[5].

B. Management Responsibilities and Research Activities

Administratively, an interagency research plan for Florida Bay is essential because of the number of agencies that have jurisdiction in Florida Bay or in ecologically connected areas. The principal federal "research" agencies are in the DOI and the DOC. Approximately 85% of Florida Bay lies within the Everglades National Park, and the National Park Service (DOI) also manages the adjacent Dry Tortugas and Biscayne National Parks. Under the Organic Act of 1916, the NPS is responsible for both protecting and preserving these unique environments. For the past several decades, the ENP has both conducted its own research in Florida Bay and funded academic researchers. Moreover, the Fish and Wildlife Service (DOI) has twelve national wildlife refuges in the South Florida regional ecosystem as well as significant responsibility under the Endangered Species Act (ESA) for endangered terrestrial species utilizing the Bay and adjacent coastal wetlands.

The remainder of the Bay lies with the Florida Keys National Marine Sanctuary, which is managed by the National Oceanic and Atmospheric Administration (NOAA/DOC) under the National Marine Sanctuaries Act. Sanctuary managers now have an explicit mandate to look upstream outside its boundaries, if necessary, to protect the FKNMS's unique coral habitats. In 1990, Congress directed EPA and the State of Florida, in conjunction with NOAA, to develop a comprehensive water-quality protection program for the Sanctuary.

The Bay is a critical nursery habitat for recreationally and commercially fished species and is the habitat of protected marine mammals and a number of threatened and endangered marine species. The National Marine Fisheries Service (NMFS/NOAA/DOC) is responsible for research on and conservation of living marine resources and their habitats under the Magnuson Fishery Conservation and Management Act of 1976, for marine mammals under the Marine Mammal Protection Act, and for endangered marine species under the Endangered Species Act. Moreover, under the Fish and Wildlife Coordination Act, NMFS is charged with representing the interests of living

marine resources in government decisions regarding land and resource management or development. NOAA/NMFS has been conducting research in the Bay since the early 1980's.

The USGS, which has no management responsibilities for Florida Bay, maintains long-term ground-water and surface-water monitoring programs in South Florida that are expanding this year through the USGS's National Water Quality Assessment (NAWQA) Program. This monitoring provides baseline data on water flow into the coastal areas. Coastal processes including erosion, deposition, and sediment transport and certain associated pollutants are evaluated by the Marine and Coastal Program of the USGS.

The principal state management agency is the Florida DEP. The state manages fisheries within its territorial waters and since 1983 has been conducting research aimed at assessing the pre-fishery recruitment of resource species which utilize estuarine and near-coastal areas. The Florida Marine Research Institute (DEP) has recently implemented a substantial monitoring program in Florida Bay and has proposed that it be significantly expanded in the next legislative session.

Last, and perhaps most critically, neither the National Park Service (DOI), NOAA (DOC), nor DEP controls the fresh water delivered to Everglades National Park and in turn to the Bay. Water delivery is regulated by the South Florida Water Management District (SFWMD) in conjunction with the Army Corps of Engineers (DOD). The SFWMD conducts its own research in the Bay and sponsors academic research through the ENP.

No one agency has sufficient management control, scientific expertise, and financial resources to independently solve the problems of Florida Bay. As concluded by Boesch *et al.*, "surely, the problems of Florida Bay are so severe and the difficulties in understanding them so challenging that Interior, NOAA, EPA, the Corps, Florida DEP, the South Florida Water Management District and Florida universities can find a way to make complementary contributions and encourage synergy in the scientific enterprise."[5] It is our hope that this plan is a major step in that direction.

C. Management Framework for Florida Bay Research

1. Interagency Florida Bay Program Management

To assure that the broad range of scientific activities planned for Florida Bay are integrated, an interagency Program Management Committee (PMC) will be established consisting of representatives from each federal agency, the Florida DEP, and the SFWMD. Each participating agency will be responsible for drafting its own detailed Florida Bay Implementation Plan. The primary role of the interagency PMC will be to review each of these implementation plans as they are completed to assure that they are consistent with this Interagency Florida Bay Science Plan. The PMC also will attempt to take advantage of the particular scientific and institutional strengths of the participating agencies. Thus the PMC will assure that each of the critical science priorities defined by the cooperating agencies is addressed by the agency or agencies best suited to do so. The science priorities will be based on research needs, which will form the basis for the scientific requirements of restoration and support any restoration plan developed by responsible agencies.

The NPS, through Everglades National Park, accepts responsibility for leading deliberations on Florida Bay restoration planning, for setting scientific priorities, and for coordinating the science programs conducted in Florida Bay. The Park's responsibility includes convening management groups and regularly communicating relevant information to agencies and institutions. The Park will use its permitting process to track the initiation of new projects and to track the reporting of results from these projects as required by the permits.

Given differences in practice and institutional experience, implementation plans may differ markedly-- e.g., some agencies award contracts, whereas others issue grants; some use panel review, and others use mail review; some conduct their own research, others primarily fund academic scientists, and still others rely upon formal government-academic cooperative units. This plan endorses no particular approach. However, the overall program must be as integrated as possible so that each implementation plan is complementary. Explicit cross-references and discussions of implementation Plans developed by the various Participant agencies will, therefore, be required in all agency implementation plans. A second important role of the PMC will be to provide additional discussion about

and review of decisions made within individual research agencies. It is assumed that PMC agency representatives will communicate recommendations made at PMC meetings to their administrative superiors. It is further assumed that, if recommended by the PMC, administrators authorized to develop Florida Bay science plans and programs for their agencies will modify current plans and introduce new elements into future plans.

Experience in multi-institutional interdisciplinary scientific programs shows that improving communication between the principal investigators is instrumental to the program's success. This is even more critical when the scientists work for different agencies and those agencies have different funding mechanisms. All agency implementation plans will at least have to provide for their scientists' participation in annual meetings of principal investigators. Funding for requisite electronic interconnection, InterNet and/or OMNET, is also highly desirable. All agency implementation plans should also provide for their scientists' participation in annual agency (or multi-agency) program reviews.

Agencies will be expected to specifically address data management in their implementation plans. Too often this is added as an afterthought, but given the multi-institutional, interdisciplinary nature of the science proposed herein, efficient integration of all the information generated is critical to the program's success. The data policy for the overall federal interagency program should be consistent with that already agreed upon for the interagency U.S. Global Change Research Program.[6] In brief, this requires early and continuing commitment to maintaining and distributing data, full and open sharing of data, archiving of data, assuring data accessibility, limiting periods of exclusive principal investigator access to an as-needed basis only, and using nationally and internationally approved standards wherever appropriate. Individual implementation plans should include a data management function and centralized databases that can be readily linked to and integrated with those implemented by other agencies.

To assure scientific quality, an interagency Technical Advisory Group (TAG) consisting of scientists representing a broad range of disciplines will be appointed to advise the PMC on the complex technical issues certain to arise in setting research priorities and planning programs. Membership will consist predominantly of principal investigators funded by the different agencies but will not be restricted to that group. Members could be added to the TAG as needed to address particular short-term needs and the TAG could also establish semipermanent subgroups to address recurrent issues such as interdisciplinary modeling, reviewing proposals for new work and evaluating scientific priorities.

2. Florida Bay Scientific Review Panel

An interdisciplinary panel of nationally recognized scientists will be invited to become members of an interagency Florida Bay Scientific Review Panel. Its role will be to provide periodic, broad, technical review of agency plans, PMC recommendations, and research results. The group will be asked to attend annual agency (or interagency) program reviews and to provide written comments and specific suggestions as to how programs can be improved. The panel will assist the agencies in setting science priorities for the Bay. Membership would be for at least four years and terms would be staggered. Membership continuity is essential to assure institutional memory--i.e., to ascertain whether programs have been responsive to the panel's review and what suggestions have proven helpful. Members of the panel will have to forego subsequent research as investigators funded under the interagency Florida Bay Science Plan.

3. General Policy Oversight

Assuming that state and regional agencies are officially incorporated into the South Florida Task Force, and the South Florida Management and Coordination Working Group, policy oversight will be provided by the Task Force through the Working Group. The Task Force has been specifically charged with coordinating the development of consistent policies, strategies, and plans and with monitoring all restoration-related research programs and activities to assure that they further the overall objective of ecosystem restoration. The Task Force was also established to facilitate the implementation of projects and programs included in the overall interagency coordinated plan for the restoration of the South Florida ecosystem.

4. The Role of the Florida Bay Working Group

As mentioned above, this document is intended to provide guidance and facilitate integration of the research to be conducted by the agencies represented in the Florida Bay Working Group and their cooperators. The PMC will communicate with the Florida Bay Working Group by reporting at Working Group meetings on the progress being made in science program implementation. The Working Group, in turn, can provide the PMC essential feedback from its primary constituents: restoration managers, environmental and economic interest groups, and the general public.

III. GENERAL BACKGROUND

Florida Bay is a triangularly shaped body of water about 2200 km^2 in area. Over 80% of the Bay lies within Everglades National Park. The Bay is bounded by the Florida mainland on the north, U. S. Highway 1 on the northeast, the Florida Keys on the southeast, and the Intracoastal Waterway between Long Key and East Cape Sable. The region west of the Park's western boundary across to the Middle Keys is also commonly considered to be part of Florida Bay. The Bay is shallow, often hypersaline and until recently, was characterized by clear waters and lush seagrass meadows covering a mosaic of shallow-water banks and relatively deeper water basins or "lakes." Deep-water channels (1 to 5 m deep) connect neighboring basins. Hardbottom habitats in southwestern Florida Bay support sponge and hard and soft coral communities. Florida Bay is known as the principal inshore nursery for the offshore Tortugas pink shrimp, Penaeus duorarum, fishery and for providing critical habitat for juvenile spiny lobster, Panulirus argus, and stone crab, Menippe mercenaria. The Bay is the site of an extensive sport fishery and supports populations of the American crocodile, bald eagle, osprey, numerous wading bird species, the bottlenosed porpoise, manatee, several species of sea turtle, and other noteworthy species. Over 200 small islands or "keys" occur in the Bay, all of which are rimmed with mangroves. Most islands have interior, irregularly flooded "flats" with calcareous bluegreen algal mats that serve as foraging and resting sites for migratory birds.

Florida Bay exchanges waters with the Straits of Florida through numerous channels between islands and with the Gulf through tidal flux and long-shore currents. In addition, some seepage must occur through the porous Key Largo Limestone. Surface fresh water flows into Florida Bay mainly from Taylor Slough and numerous small streams to the east. Groundwater seepage from the peninsula is believed to be a major but poorly quantified freshwater input. Large flows of fresh water from the Shark River Slough reach Florida Bay only after mixing with Gulf of Mexico water and flowing eastward around Cape Sable. For most of the western half of the Bay, currents are presumed to move in a southerly direction, although few direct measurements support this pattern. Currents on the Bay side of the Upper and Middle Keys presumably flow to the southwest, resulting in a net flow from the Bay toward the Atlantic side through the channels between the Keys. Thus, constriction of the channels between the Keys could reduce net flow of water through the Bay.

The complex bottom topography of the Bay divides it into various subenvironments that have different physical and chemical conditions. The uppermost part of the Bay consists of a number of semi-enclosed sounds that are partly isolated from one another. Southwest of Blackwater and Little Blackwater sounds (northeastern Florida Bay proper), the mud shoals and islands become less numerous, and the area is shallow. Toward the Gulf of Mexico on the mainland side, mud banks increase in width and depth. On the Keys side (toward the Atlantic), the mud banks are narrower and encircle deep, hardbottom "lake" areas.

Northeastern Florida Bay is strongly influenced by seasonal freshwater runoff. Salinities range widely, from brackish to salinities greater than seawater. The interior of Florida Bay is characterized by extremely restricted circulation and widely fluctuating salinities and temperatures; evaporation exceeds freshwater inflow and direct rainfall. Flushing is slow except for occasional wind-driven transport across shallow boundary sills. In contrast, along the western margin of the Bay, temperatures are relatively moderate and salinities fluctuate near oceanic levels.

The rainy season, May through October, coincides with a seasonal rise in sea level. As the sea level falls (about 15 cm), water of lower salinity reaches well out into the Bay. In addition to this seasonal salinity variation, drought/flood cycles also affect annual salinity ranges. The effects of such cycles can be pronounced. For example, August salinities in northeastern Florida Bay may range from 15 ppt to 50 ppt in successive years, depending on

rainfall/runoff conditions. Salinities approaching 70 ppt are reported to have occurred in the central Bay during the droughts of the early 1950s when freshwater supply to the northern Bay was reduced to meet agricultural and municipal requirements.

The Bay is underlain by a floor of extremely flat and permeable Pleistocene limestone that was formed between 125,000 and 145,000 years ago during the last interglacial. This floor gently slopes to the southwest, so that during the last glacial melting, the Bay was flooded from southwest to northeast as sea level approached its present position. During the past 4500 years, peat and carbonate mud have accumulated to form a series of Holocene intertidal mud banks and mangrove islands that now dissect the Bay into shallow basins locally termed "lakes." The present configuration of mud banks is the result of complex deposition and erosion processes that form coastal levees, ponds, storm ridges, migrating islands, and mud banks at various locations throughout the Bay. These sediments are formed from organisms living in the Bay at rates that have easily kept up with sea-level rise during the past few thousand years. Rapid sedimentation may be further restricting the Bay; however, large volumes of sediment are also exported from the Bay, and it is unclear if sedimentation is keeping up with the relatively rapid sea-level rise that has occurred during the last century.

Over the past decade, a number of biological, chemical, and physical changes in Florida Bay have been observed by scientists, tourists, and fisherman who frequent the Bay. Seagrasses in western Florida Bay, principally turtlegrass (Thalassia testudinum) have been dying since the summer of 1987 and continue to as of March 1994. Mass mortality of this magnitude has not been observed previously in Florida Bay nor has it been reported in the scientific literature on tropical seagrasses. Initially, three causes of seagrass die-off were proposed.[5] First, the synergistic effects of several long- and short-term factors appear to have caused a production/respiration imbalance. Second, the observed contagious distribution of die-off patches and the rapidity of the die-off process suggest that a pathogen was the proximate cause of seagrass die-off. Third, eutrophication was considered a possible cause of die-off, although evidence of eutrophication was observed prior to seagrass die-off in Florida Bay.

Several adverse trends have accompanied the die-off, most notably declining water quality as algal blooms have increased in intensity and duration. Declines in the pink shrimp and sport fisheries and the die-back of sponges threatening the lobster fishery have also coincided with seagrass die-off in the Bay.

Conditions that have been present in the Bay since 1988 appear to be associated with, and may result in some way from, seagrass die-off. For example, Florida Bay has had plankton blooms since the seagrass die-off in 1987, but not before. The blooms have reoccurred each year and have become steadily bigger and more persistent as the seagrass die-off has spread to relatively higher-energy areas of the Bay such as Sandy Key Basin. The exposed sediments are resuspended daily by the tides and frequently by winds, increasing turbidity and probably releasing nutrients into the water column.

The most compelling hypothesis for the cause of seagrass die-off involves long- and short-term processes, both involving alteration of freshwater supply to the Bay. Over the long-term period of a half century or more, the diversion of fresh water by upland water management has contributed to increasingly marine-like conditions in Florida Bay. Knowledge of the comparative biology of the seagrasses suggests that this trend has favored the dominance and growth of turtlegrass over other species.

Over the past three decades, Florida Bay has experienced fewer hurricanes compared to the long-term record in South Florida, and water management has diverted peak storm flows that otherwise would have reached Florida Bay. Both trends have had the effect of reducing disturbance of the Bay benthos and sediments. The absence of these high-volume inflows has led to stabilization and deepening of bottom sediments and heavy accumulation of seagrass detritus.

On the time scale of several years, high salinities and elevated water temperatures have been measured in Florida Bay at levels that are understood to cause physiological stress in seagrasses. Both stresses may have contributed to seagrass die-off. In addition, since August 1992, Florida Bay has experienced Hurricane Andrew, the "storm of the century" (in March 1993), and the wettest January (1993) on record. Each of these events, as well as the severe 1989 freeze, may have contributed to the present status of Florida Bay.

IV. ORGANIZING STRATEGY

A. Restoration Perspective

The management objective for Florida Bay is to restore it to a naturally functioning ecosystem. The restoration process and the degree to which management can effect change define, in large part, the focus and priorities of the scientific activities supporting Florida Bay restoration.

Restoration as a goal assumes, *a priori*, that the Bay has been impacted by man. The current perception of Florida Bay is that the Bay is a system in decline. Seagrass die-off, persistent plankton blooms, extensive turbidity, and declining commercial and recreational fisheries are thought to be the consequence of accelerating human population growth, land use changes, the expansion of agriculture, and the development of increasingly invasive and environmentally destructive water-management practices in the headwaters of Florida Bay. Although it is probable that the Bay is, and has been. strongly impacted by man's activities in South Florida, cause-and-effect relationships have not been rigorously determined. Long-term natural changes have not been clearly separated from those that result from human intervention. Various hypotheses have been put forth to explain current problems in the Bay. These are not mutually exclusive. However, limitations of the means available to direct change in Florida Bay strongly argue for a research program that emphasizes hypotheses linked to manipulation of the quality, quantity, timing and distribution of freshwater inflow to the Bay.

Defining a realistic restoration endpoint is an important step. To what condition, to what status, do we seek to return the Bay? In one sense, restoration implies that the natural ecological condition for the Bay is known or can be known. Since 1988, Florida Bay has definitely differed from the clear-water, turtlegrass-dominated system well documented to be characteristic of the Bay over recent decades. But a reliable historical picture of what Florida Bay was like in its natural, unregulated condition is unavailable. The era of water management began more than 100 years ago, when few scientific data were collected. A major challenge, therefore, is to determine to what extent any reconstruction of Florida Bay to conditions that existed prior to human intervention constitutes an achievable restoration target. The present and future regional environment of which Florida Bay is a part may further constrain an historically-based definition of successful restoration.

Management options and capabilities with regard to restoration are regional in context, and the principal available options relate to the controlling of physical or chemical factors (e.g., manipulation of water deliveries, improved agricultural practices, nutrient removal). In contrast, the success of restoration will be measured in biological terms. For example, the Bay functions as a nursery ground for pink shrimp, as critical habitat for numerous endangered species and as the foundation of the recreational fishing industry throughout South Florida, including the Keys. These and other ecological functions must serve as criteria for evaluating the success of Florida Bay restoration. Thus, interdisciplinary research must link physical and chemical factors to biological processes.

Implicit in the restoration goal is the intention to modify or eliminate anthropogenic processes harmful to the Bay and thus regain the natural ecosystem. Absent from this goal is any intent to modify the Bay's natural function to enhance the prospects of a single species or to maximize economic return. This perspective has guided us in developing the scientific goals and objectives described below.

B. Scientific Goals and Objectives

The science program needed to accomplish successful restoration must be long term and goal oriented and be committed to the integration of emerging results into the management decision-making process. The research program, discussed in detail below, addresses several broadly complementary research objectives. It will provide the basic understanding of the Florida Bay ecosystem so that appropriate plans for restoration can be determined. Specific objectives include the following:

1) Developing an understanding of the condition of Florida Bay prior to man's significantly altering it. This information will help provide an "idealized" target for restoring Florida Bay. Although full restoration may prove impossible, an historical understanding provides a perspective on the extent and effectiveness of management restoration actions.

2) Separating anthropogenically induced changes in Florida Bay from natural system variation. Both natural disturbances (e.g., hurricanes, freezes) and long-term climate processes (drought cycle, sea-level rise) have strongly influenced the structure and function of the Bay. These same processes may mask or exacerbate the effects of anthropogenic forces on the Bay. Therefore, it is essential to understand anthropogenic effects within the context of natural system function and variation.

3) Developing a basic understanding of the ecology of Florida Bay by evaluating alternative hypotheses.

4) Developing the capability to predict the response to perturbation of a subset of species or ecological processes that collectively may be considered indicators of key processes or functions of Florida Bay. Restoration of Florida Bay will require choosing among alternative management actions based on ecosystem responses. Relating the responses of these indicators to potential management alternatives is one way in which an ecological understanding of the Bay becomes a key ingredient in the decision-making processes of agency managers.

C. Research Approach

If a science program is truly to support restoration efforts in Florida Bay, monitoring, research, and modeling elements must be tightly linked, as illustrated in Figure 2. By monitoring, we can track critical ecosystem parameters and support long-term research and modeling efforts by providing baseline data and the means to calibrate and validate models. Further, after management decisions have been made, monitoring data will be used to evaluate the effectiveness of these decisions. Through research, we will develop an understanding of the physical and biological processes regulating Bay ecosystem status by establishing statistical associations, defining and testing conceptual and research models, evaluating cause-and-effect relationships through experimentation, and synthesizing available information. Computer simulations that synthesize our best understanding of the Bay's ecology will be developed to a stage that allows for predictions of system responses to change, hindcasting of historical conditions, and selection of management alternatives. Regular feedback between program elements is needed to yield increasingly reliable computer simulations of the Florida Bay ecosystem for use by management.

D. Linking Research and Resource Management

Modeling is central to the process of linking research findings with resource management decisions that will implement restoration actions. Hydrology models and biological models will be used to develop and select appropriate management alternatives for restoring the Bay. The feasibility of a modeling approach already has been demonstrated. For example, the hydrology of Taylor Slough, at the headwaters of Florida Bay, has been modeled. These models are being used to predict the hydrologic effects of structural or water-delivery modifications of the existing canal system or to predict water conditions in the absence of canals. Biological models should be further developed so that they can predict the response of "representative" species to hydrologic conditions established by water-management alternatives. The current Army Corps of Engineers General Reevaluation Report and Environmental Impact Statement for Canal 111 (C-lll GRR) is one element in a process whereby preferred structural and operational water-management alternatives would be selected and implemented. Analyses of hydrologic and biological monitoring data would allow researchers to evaluate the system's actual response to the resultant hydrologic conditions and would provide the basis for evaluating alternatives and refining models.

Conceptually, this process is iterative. However, the relatively high level of natural variation in the Florida Bay ecosystem; the expected relatively slow response of the flora and fauna of the Bay to changed hydrologic conditions; and the time required to plan, fund, and construct canal structures for water deliveries, argue that restoration of Florida Bay will be a long-term process and that the first iteration must achieve significant restoration benefits. The system's inherent complexity also supports the emphasis in this strategy placed on predictive modeling as the best tactic for testing and evaluating alternatives.

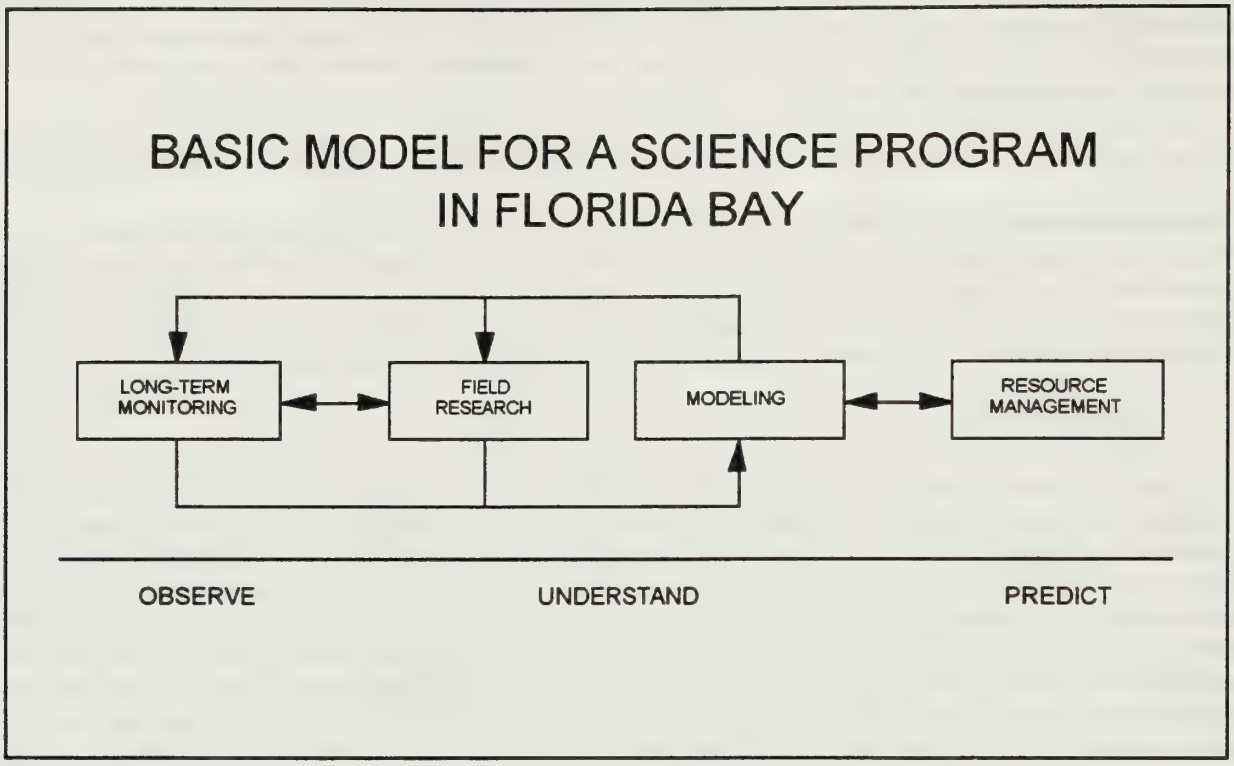


Figure 2

V. MAJOR RESEARCH TOPIC AREAS

Management decisions on restoration must be based on scientific understanding of the Bay, of the changes the Bay has undergone, and of the various natural and anthropogenic processes determining the Bay's present and future status. The following four comprehensive topics describe the major gaps in our present understanding of the Florida Bay ecosystem, our continuing data needs, and the necessity of improving our predictive capacity. Carrying out these specified tasks will provide answers to the questions that need to be answered if restoration is to proceed on a scientifically sound basis. In order to focus in this document on programmatic needs rather than on technical procedures, no attempt was made to provide technical references. Rather, the reader is directed toward the following compilations for further information: the special issue of the Bulletin of Marine Sciences[7] published in 1989, the SWIM Plan for the Everglades[8], and the bibliography of the Science Sub-group report to the Federal Restoration Working Group[9].

A. Water Budgets, Circulation Dynamics, and Salinity

Three interrelated aspects of Florida Bay water budgets and circulation dynamics are considered here, particularly as they relate to salinity patterns and trends in the sub-environments of the Bay. Quantitative knowledge of the mass balance and circulation dynamics of Bay waters is essential to understand the causes of observed biological and chemical patterns within the Bay and their relation to processes outside the Bay.

1. What has been the relationship of surface water and groundwater flows through the Everglades to the salinity of Florida Bay? How has this relationship changed in the past, and how is it expected to change with future management plans?

Under present conditions, the natural flows of fresh water into Florida Bay are much reduced. The Natural System Model indicates that for the 1965-1989 period, as the system is currently managed, less than one half of the "natural" surface-water flow through Taylor Slough was discharged into Florida Bay (32,500 ac-ft/yr versus 82,000

ac-ft/yr). The flow of Shark River also seems to have been significantly reduced from "natural" conditions, although flows during 1991 and 1992 were nearly three times the annual average for the 1980s. How changes in freshwater delivery through the Shark River Slough (whose flow is an order of magnitude greater in volume than the natural flow through Taylor Slough) have affected Florida Bay is not well known.

Salinity records, anecdotal evidence, and predictive models linking groundwater levels in northern Taylor Slough to salinity in Little Madeira and Joe bays provide evidence that salinities in northeastern Florida Bay have increased as a result of reductions in freshwater inflow. Salinities have been elevated since at least the mid-1950s and on occasion have been markedly hypersaline (to 70 ppt). The relationship between salinity levels in the open central Bay and reductions in freshwater discharge is unclear. Discontinuous salinity measurements made in the more open central and western Florida Bay from 1955 through 1990 show no obvious changes in salinity, although hypersaline conditions have characterized the northcentral and northwestern Bay at least since the mid-1950s. The historical record, however, indicates that large increases in freshwater inflow during extended periods of heavy rainfall (e.g., during 1983) can eliminate hypersaline conditions in the eastern and central Bay, whereas hypersaline conditions developed during dry years, even before most of the flow through Taylor Slough was diverted down the C-111 canal.

Key Research Needs

The goal of the physical oceanographic research and modeling effort will be to collect data and to develop models sufficient to predict, both for the Bay as a whole and for its major subbasins, the influence of varying freshwater inflow and precipitation on circulation dynamics and salinity patterns.

Specific Tasks

i. Determine the rates and effects on water quality of freshwater flows through the Taylor Slough rivers and channels, canals and adjacent panhandle area into Florida Bay. The spatial and temporal variation across this transition zone must be quantified for a range of wet and dry hydrologic regimes. A sampling system is needed so that episodic events and low flow conditions are accurately characterized. Salinity/runoff relationships must be developed so that effects on inflow rates of differing water-delivery policies can be quantitatively predicted.

ii. Quantify the importance of groundwater as part of freshwater input and as a factor influencing water quality in Florida Bay. Groundwater contributions to Florida Bay are one of the most poorly known components of the water budget. Because of the difficulty of measuring it, groundwater is often estimated from hydrologic models. Some field measurements are essential to calibrate and verify models. Estimates of flows through the Buttonwood Ridge and other components of the mangrove fringe and associated boundary areas in the southernmost mainland are particularly critical.

iii. Determine the linkage between Shark River Slough discharges and Florida Bay. Temperature, salinity, and current measurements in the tributaries of the Slough and perhaps tracer studies of nearshore currents between the main Shark River estuaries, Cape Sable, Sandy Key Basin, and the Flamingo area are needed to permit quantification of the net flux of water and salinity into the Florida Bay. Data are needed over several annual hydrologic cycles in order to understand seasonal and interannual effects.

iv. Determine the spatial pattern of salinity in Florida Bay and its relationship to freshwater inflow and climatic variation. Consideration should be given to supplementing the existing salinity-sensor network with automated salinity sensors and/or augmenting these measurements with micro-radiometry-based remote sensing of surface salinity when operational systems become available. Efforts should also be made to determine historical salinity patterns in Florida Bay.

v. Determine evaporation rates from the Bay and the canals and characterize their temporal and spatial variations.

vi. Improve monitoring of rainfall. The precision of traditional rain gauges is poor, but their performance could be improved by judicious use of radar- and acoustic-based measurement methods.

vii. Develop a circulation dynamics model for Florida Bay. The model should incorporate existing model structures from other water bodies as much as possible and be capable of simulating circulation and transport across the Bay as a whole, both within the major sub-environments and within local basins. Development of the model should proceed cooperatively with ecological modeling efforts so that model structure and outputs are accessible for addressing questions on the movement, recruitment, and distribution of marine organisms and on the transport, accumulation, and cycling of nutrients and contaminants. Adequate answers to these questions may eventually require a three-dimensional model, but until that is demonstrated. a two-dimensional model will suffice.

viii. Integrate circulation models of Florida Bay with larger-scale physical oceanographic, hydrological, and meteorological models that provide the Bay model with its boundary conditions and forcing functions. Erosion and sea level rise are two important continuing processes that must be explicitly tested in a complete model. A mesoscale meteorological model that could improve prediction of precipitation intensity and distribution would be invaluable to both circulation and hydrological modeling.

2. What is the effect of the relative lack of storms over the past three decades on the buildup of sediments, nutrients, and organic material in the Bay?

Hurricanes are believed to resuspend and transport sediments and organic detritus out of bays. Few, if any, hurricanes have significantly affected Florida Bay since 1965. In the absence of these erosional events, production of sediments and their trapping by seagrasses and mangroves could reduce water circulation, thereby affecting salinity distribution, water temperature, nutrient supply, habitat, and movement of marine organisms.

Quantitative evidence on the effects of storms is lacking, but qualitative observations suggest that the reduced occurrence of major storms has resulted in significant accumulation of calcareous muds and entrained nutrients.

Key Research Needs

Because Florida Bay is a shallow-water system, sediment dynamics are particularly important. Much of the primary production in the Bay is benthic, and resuspended sediments can markedly reduce photosynthetic potential. The fine-grained, shallow sediments are susceptible to physical and chemical alteration by the forces of weather and biological and human activity. Despite the importance of sediments, however, information on their dynamics, composition, and spatial patterning is insufficient for reaching a quantitative understanding of their role in the changing conditions of Florida Bay.

Specific Tasks

i. The bottom topography of the Bay has not been systematically examined in three decades. Plotting the bottom contours on a grid fine enough to delineate the basins and their interconnections is essential both to document changes in water depth and to supply information for circulation modeling. Whether this can be done by compiling existing data or whether extensive new measurements are required cannot be determined in advance. The answer may depend on the degree of sensitivity of various models to water depth. The scale of the bathymetry data should be appropriate to circulation modeling requirements.

ii. Determine the main components of the sediment budget for Florida Bay, including exchanges with connected waterbodies, inputs from the mainland, and accumulation within selected subbasins.

iii. Determine the physical and chemical composition of the sediments, the pattern of composition throughout the Bay, and the variability in composition over hydrologic cycles and in relation to storm events.

iv. Determine the historical pattern of sediment accumulation and composition. Bay sediments should be cored following standard procedures. Cores should be subjected to radioisotope dating, stable isotopic analysis, and any other physical or chemical analyses deemed to be helpful in reconstructing historical Bay conditions.

3. What have been the effects in Florida Bay of increased residence time of water caused by restricted water flow through channels between the Keys, shoaling, and reduced freshwater inflows?

Little is known about the residence time of water within Florida Bay, although a decrease in the flushing rate could have widespread consequences to this ecosystem. As a result of landfilling along the Keys, an increase in residence time is likely to have occurred. Mudbank shoaling may also have further decreased flushing of isolated basins in the Bay. But the extent to which flushing may have been decreased by channel constriction or shoaling is unknown. Except for the regions of the northeastern Bay directly affected by the Taylor Slough discharge, reductions of freshwater flows may have had little impact on the flushing rate of the Bay. Salinity could have increased through more evaporative concentration of Bay water, especially because freshwater inputs have decreased. Greater stagnation could also increase temperature extremes, increase concentrations of plant nutrients, and disrupt recruitment of planktonic fish and invertebrate larvae.

If one assumes that flow through Taylor Slough has been reduced by 50,000 ac-ft/yr and that the average depth of the Bay is about 1 m, the total diverted flow during a full year would, on the average, be sufficient to replace only about 10% of the volume of the Bay. Tidal and wind-driven flows surely exchange far more of the Bay's volume, probably on the scale of days. Also, because the Bay is shallow and vertically well mixed, there should be no appreciable gravity flows of the type found in deeper, stratified estuaries by which the flushing effect of freshwater inputs is greatly magnified.

Specific Tasks

i. Determine the effect on circulation of shoaling caused by sediment accretion on the mudbanks. This could have a very great effect on the flushing rates for basins in the central and eastern Bay, but this effect has not been measured or estimated. A program of field-data collection in selected subbasins is needed. This program should quantify both incremental processes and mass movements that may accompany episodic climatic events. Since the data are valuable for circulation modeling, compatibility with models is important.

ii. Determine the relative importance of tides, winds, and altered freshwater inflows on flushing rates and exchanges with adjacent waterbodies. Data are needed on time scales of days, months, and years across a range of wet and dry cycles to adequately parameterize circulation models.

B. Water quality and nutrient cycling

1. What are the sources, quantities, and ecological effects of "external" nutrients introduced into Florida Bay?

The exchange of nutrients between Florida Bay and adjacent regions ("external" dynamics) and the cycling of nutrients within Florida Bay ("internal" dynamics) underpin the entire Bay's ecological structure and function, the occurrence of algal blooms, seagrass mass mortality, and the sustenance of critical species. We currently have little understanding of the rates of these
processes or the mechanisms that control the rates. Furthermore, we have little understanding of how these dynamics have naturally varied in the past or how human activities have affected them.

Algal blooms in the Bay appear to be similar to blooms caused by anthropogenic nutrient loading, which has been observed in estuaries throughout the world. However, the sources of the nutrients that sustain Florida Bay's blooms are unknown. Although it is likely that the blooms are in part sustained by nutrients derived from decomposing seagrass detritus resulting from seagrass die-back events, the blooms may also depend upon the supply

of external nutrients from agriculture, fertilizer mining, or sewage in the Keys. Changes in the input of nutrients to the Bay may also result indirectly from altered hydrology; changes in freshwater flow and salinity intrusion may have reduced the retention of nutrients within the Everglades and mangrove ecosystems. Finally, the Bay may appear eutrophic not because the total inflow of nutrients has increased, but because the residence time of source waters with high concentrations of nutrients has increased with diminished flushing rates (see above), or because internal sinks of nutrients have decreased.

Understanding the exchange of nutrients between Florida Bay and adjacent regions requires an integrated effort to 1) measure the flux of nutrients across the Bay's boundaries; 2) characterize the physical, chemical, and ecological mechanisms that regulate these fluxes; and 3) integrate this information into a regional landscape model of nutrient transport and transformation. The major boundaries that must be considered are between Florida Bay and the atmosphere, the northern coast, the Gulf of Mexico, and the Florida Keys. Thus, an effort to understand the nutrient dynamics of the Bay must be integrated with efforts to accurately describe surface and groundwater inflows from the Florida mainland, the exchange of Bay water with the Gulf of Mexico and through passes in the Florida Keys, and atmospheric deposition rates.

Key research needs

Atmospheric deposition of nutrients is known to be a significant nutrient source in many coastal ecosystems and may be particularly important in Florida Bay because the Bay appears to have been oligotrophic throughout much of its history and is surrounded by relatively low-nutrient wetlands and water bodies. A key research need is to determine deposition rates and atmospheric nutrient sources.

Specific Tasks

i. Measure the deposition of wet and dry nutrients into the Bay.

ii. If these inputs are important, relative to other inputs, determine the sources of these nutrients and estimate their historical variability.

Additional research is needed to determine the exchanges of nutrients between the Bay and the Gulf of Mexico and the degree to which these exchanges have been altered by human activity. The Gulf of Mexico may be an important nutrient source for the Bay for several reasons. First, there appears to be a net advection of water from the Gulf into the northwestern Bay. Second, the Gulf ecosystem, like most marine ecosystems, is probably N limited, and thus has a small "excess" of P. relative to N. Third, the Florida fertilizer industry may enrich Gulf waters. Fourth, organic P flows into the Gulf from the western Everglades and the dense mangroves along the southwest Florida coast. Although this water has a high N:P ratio, the absolute quantity of organic P delivered to the Bay may nevertheless be significant. This N source may, furthermore, stimulate algal blooms and benthic macrophytes west of the Bay, where N limitation may be more prevalent than in the Bay.

Specific Tasks

i. Continue and extend water-quality monitoring in the western Bay and southwestern Florida coastal waters on both a regular schedule and on an event basis, so that exchanges during storm events can be determined.

ii. Monitor the distribution, transport, and nutrient demands of algae along the western Bay boundary.

iii. If budgets suggest that Gulf waters are an important nutrient source, investigate the import and export of nutrients through mangrove ecosystems in representative sectors of the southwest Florida coast and estimate their historical variability (see mangrove subsection below).

Determining the exchange of nutrients between the northern Bay and the South Florida wetlands and the degree to which these exchanges have been altered by human activity is also needed. No measurements have been made of the flux of organic or inorganic nutrients across the salinity transition zone of the coastline. The rapid appearance and disappearance of dense macroalgal clumps in streams that feed into the northeastern Bay suggest

that the export of nutrients from this zone may at least be locally important. The N:P ratio of this source is probably high, and the mechanisms altering this ratio have not been studied in the transition zone.

Specific Tasks

i. Estimate nutrient flux by measuring surface and groundwater flows into the Bay and their nutrient concentrations across the entire northern coast.

ii. Continue water-quality monitoring in the northern Bay.

Another key to understanding the inflow of nutrients to the Bay from both the southwest and south Florida coasts is understanding the ecology and biogeochemistry of mangrove ecosystems. Along with the Everglades marshes, mangroves are a biological filter through which much of the freshwater inflow passes before reaching the Bay. Despite low P inputs from the Everglades to the mangrove forests, the mangrove forests are highly productive, and their standing stock and litter represent a potential nutrient source. A large export of nutrients from these systems either on a regular (e.g., seasonal) or episodic basis (e.g., freezes and hurricanes) is possible. Furthermore, the extent to which the retention or release of nutrients by coastal wetlands and mangroves has changed in response to human activities and climate change (e.g., increased intrusion of seawater resulting from sea-level rise and freshwater diversion) is unknown.

Specific Tasks

i. Measure water flow and the import and export of dissolved and particulate nutrients at selected sites, especially after episodic disturbances.

ii. Investigate the sources of nutrients for mangrove trees (marine, inland, sediments).

iii. Investigate the effects of altered salinity regimes upon nutrient dynamics within mangrove and marsh systems, including effects on decomposition, mobilization from. and immobilization in sediments.

iv. Assess recent changes in the distribution and biomass of mangroves along South Florida coasts (see section C below).

v. From Bay sediment cores, assess changes in the historical accumulation of organic matter derived from mangroves and other terrestrial sources.

Research is needed to determine nutrient fluxes through passes in the Keys and the input of nutrients to the Bay from sewage in the Keys. Sewage effluent from the Keys is known to have caused localized eutrophication. The regional importance of this nutrient source is not known. This may be of more direct significance to the Florida Keys National Marine Sanctuary. Researchers sponsored by the Sanctuary should be directed to undertake the following in collaboration with the Florida Bay program.

Specific Tasks

i. Monitor the flow of water and organic and inorganic nutrients through the Keys' passes.

ii. Estimate the input of anthropogenic nutrients from the Keys.

2. What are the rates of nutrient exchange between the sediment and water column within Florida Bay, and what controls the magnitude and direction of these fluxes?

Because of Florida Bay's shallow depth and the carbonate composition of its sediments, the internal dynamics of nutrients within the Bay are regulated by sedimentary processes. Given the Bay's shallow depth and historical clarity, seagrass primary production has been considered the basis of overall Bay productivity. However, the shallow depth of the Bay also results in high resuspension rates for unconsolidated sediments (see section C).

Suspended sediments not only decrease light penetration through the water, but also scavenge particle-reactive solutes such as inorganic phosphates from the water. The carbonate composition of these sedimentary particles is important because the particles have the potential to bind inorganic P under both oxic and anoxic conditions. Thus, apparent P limitation in the Bay may be due not to biological utilization but to loss to the sediments. We need to know if mechanisms exist whereby this P can be released.

One such mechanism may involve the normal physiological activities in the seagrass rhizosphere. It is possible that seagrasses exude organic acids or sustain a microbial consortium that mobilizes phosphorous. Thalassia may be particularly important in this regard because this species has a deep and extensive root system. It has thrived in recent decades in waters with salinities that were higher than those found before the water diversion from the Everglades (see above); as a result P mobilization from the sediment may have also been accelerated.

Other mechanisms that may alter the extent to which P is bound to or released from carbonate particles may involve the surface chemistry of carbonate particles, in particular their organic coatings. Seagrass and mangrove die-offs and wetland perturbation may have altered organic inputs into the Bay. Salinity itself may play a direct role because ionic strength is an important variable affecting surface reactions.

Key Research Needs

Key research needs include estimating rates of benthic nutrient fluxes at various sites in order to accurately estimate flux for the Bay as a whole, assessing the importance of different mechanisms upon the mobility of nutrients bound in sediments, and assessing how the internal nutrient cycles of Florida Bay may have changed during past decades and centuries.

Specific Tasks

i. Measure net fluxes in benthic chambers and from sediment cores.

ii. Measure rates of detrital decomposition in healthy and declining seagrass stands.

iii. Investigate the processes by which seagrasses, particularly Thalassia, assimilate nutrients from sediments and assess the effect of environmental (e.g., light, temperature, and salinity) conditions upon observed rates.

iv. Investigate the chemical and microbial processes that mobilize or immobilize nutrients in the sediments.

v. Develop a model of the benthic subsystem that includes seagrass populations and all the nutrient pools and pathways potentially significant to the overall nutrient cycle.

vi. Determine the contribution of nutrients from tidal pumping nutrient-rich subsurface water from the permeable limestone floor to the water column.

vii. Obtain and date sediment cores; estimate rates of sediment and nutrient accumulation and their temporal variation.

3. What are the rates of nutrient assimilation by phytoplankton in the Bay, and what limits the growth of the phytoplankton assemblage?

Pelagic primary production has increased in relative importance in much of the Bay. With continued seagrass die-off, sediment resuspension has increased, thus increasing light extinction by inorganic particles. The situation may be perpetuated by a feedback loop whereby dense microalgal blooms inhibit seagrass recovery by absorbing light and thereby increase sediment resuspension, furthering their own competitive advantage. Pelagic dynamics that have been heretofore ignored now need to be studied.

Key Research Needs

Key research needs include developing basic information on the phytoplankton ecology of the Bay and assessing the importance of factors other than nutrients upon the development and maintenance of algal blooms.

Specific Tasks

i. Measure the distribution, biomass, productivity, and composition of the phytoplankton community.

ii. Monitor light distributions in the water column.

iii. Determine photosynthesis versus light extinction curves for the dominant phytoplankton species.

iv. Measure nutrient uptake kinetics of the dominant phytoplankton species and conduct experiments to study phytoplankton nutrient limitations.

v. Measure zooplankton biomass and grazing rate. vi. Measure benthic filter feeder biomass and grazing rate.

vi. Measure benthic filter feeder biomass and grazing rate.

vii. Estimate the effect of sediment resuspension upon light and nutrient availability in the water column.

viii. Use the sedimentary record to determine whether extensive phytoplankton blooms occurred in the past and if so under what conditions.

ix. Develop a model of water column processes that is coupled to the benthic model (and sediments) and that incorporates both pelagic nutrient dynamics and grazing losses.

4. What are the sources, quantities, and effects of toxic pollutants introduced into the Florida Bay ecosystem?

Pollutants are a common problem in coastal ecosystems, but given the relative isolation of Florida Bay from extensive municipal and industrial development, toxic pollutant inputs from sources other than local agriculture should be minimal. However, we currently have little information on inputs, pathways, or effects of toxic pollutants in the Bay. Because it is likely that management actions taken to restore freshwater inputs to the Bay will also affect pollutant dynamics, we need to establish a monitoring program before these changes are made.

Mercury is a pollutant of special concern. It is a human health hazard because of its toxicity, persistence, and the extent to which it bioaccumulates in tissues and biomagnifies through the food chain. It has also been found at high levels in the Everglades biota, including fish in northeastern Florida Bay. Thus, mercury contamination in the Bay may be increasing.

The other major group of toxic pollutants of particular concern are synthetic organic compounds that are used as pesticides both in mosquito control and in South Florida agriculture.

Key Research Needs

Key research needs include determining the extent, pathways, and history of mercury contamination in the Bay; determining the flux of dissolved and absorbed toxic organics into the Bay; and determining the atmospheric flux of pesticides into the Bay. Monitoring mercury concentrations in selected Florida Bay biota is a prudent first step given the problems already evident in the Everglades. Monitoring all or most of the toxic organics used in Florida agriculture is unnecessary. Rather, attention should be paid to pesticides that are used in large quantities, are mobile in surface water or groundwater, are relatively persistent, and are known to have significant ecological effects. A Contaminants Advisory Committee should be established to determine which compounds warrant study.

The main concern in determining atmospheric flux is direct aerial input because pesticides are extensively used for mosquito control in Dade and Monroe counties. This may have a local effect at the time of application. Larval crustaceans are particularly sensitive to such chemicals, and thus, the timing of these doses and their distribution in the Bay warrant further study.

Specific Tasks

i. Monitor tissue concentrations in fish and organisms from upper trophic levels, e.g., crocodile eggs.

ii. Monitor water column mercury concentrations and chemical forms in water entering the Bay and at selected stations within the Bay.

iii. Measure atmospheric mercury inputs.

iv. Measure the historical record of mercury accumulation in the Bay from sediments, peat, or corals.

v. Monitor mercury concentrations in canals and other surface water and groundwater.

vi. Monitor water and sediment mercury concentrations at a set of Bay stations.

vii. Monitor mercury concentrations in those fauna that may integrate the variability of exposure in the Bay (e.g., filter-feeding bivalves), those species that may have high body burdens (e.g., from upper trophic levels or those with an especially high fat content), and those species that may be particularly sensitive to pesticides (e.g., the osprey).

viii. Monitor the time, amount, and extent of pesticide application (including information on not only the "active" compounds but the associated solvents) and establish a centrally accessible data base.

ix. Relate actual pesticide application to potentially critical areas and periods within the Bay, considering the life history and recruitment of key species.

x. Monitor the body burden of the pesticide compounds applied to the larvae, juveniles and adults of key species (e.g., pink shrimp).

xi. Perform special studies to assess specific pesticide application events.

5. What is the cause of turbidity in the Bay, and what is its effect on Bay water quality?

Increased turbidity is the most conspicuous change in the Bay since 1987. Declining water clarity has the potential to shift Florida Bay away from a system dominated by benthic primary production towards one dominated by water-column productivity. This critical area needs to be researched further.

Specific Tasks

i. Determine biological components of turbidity.

ii. Determine contribution of resuspended sediments to turbidity and determine how suspended sediments relate to sediment transport, erosion, and deposition.

C. Seagrass, Mangrove, and Hardbottom Habitats

The three major habitat types in Florida Bay are discussed here. Each has undergone significant change, particularly seagrass meadows. Historically, seagrasses have been the dominant primary producers in Florida Bay. In addition they structure the benthic habitats by providing refuge to important consumer species in their vulnerable early stages and by consolidating otherwise readily resuspended carbonate sediments. Recent changes in seagrass

distribution and abundance throughout Florida Bay constitute a major shift in the functional dynamics of the ecosystem. The resultant effects on organisms, food chains, processes, and the Bay as a whole are of major concern for all three habitat types.

1. What environmental factors explain the observed distribution of seagrasses within the Bay and caused the recent die-off?

Reduced freshwater flow into Florida Bay resulting from drought and diversion of upland runoff is thought to have caused significant increases in average salinities in the interior basins of Florida Bay. The higher salinities have allowed Thalassia testudinum beds in the northcentral and western Bay to develop very high densities and biomass in basins that historically supported a more diverse, more typically estuarine seagrass assemblage (e.g., Halodule, Ruppia, and Thalassia).

Nonetheless, seagrass populations of Florida Bay appeared to be thriving as late as 1984. Leaf defoliation of bank-top seagrasses and seagrass die-off was observed during the summer of 1987. Seagrass die-off spread rapidly, affecting primarily but not exclusively the dense beds of north-central and western Florida Bay. It is speculated that the shallow waters and restricted circulation of Florida Bay, coupled with diminished freshwater flow from the Everglades and the exaggerated near monospecificity attained under these conditions, amplified the effects of natural temperature and salinity variations and thus caused large-scale die-offs.

Key Research Needs

The first step is to fully understand the causes (both natural and anthropogenic) of the observed changes and the relationships between these factors. Detailed physiological, ecological, and demographic information is essential if we are to develop a predictive capability. Estimating future changes in seagrass distribution, abundance, and dynamics is an essential component of the scientific basis for restoration management.

Specific Tasks

i. Determine current seagrass species distributions, abundances, and biomasses to assess possible large-scale spatial changes that have taken place since the 1983-84 survey. Incorporate these data into a GIS database.

ii. Determine the effects of salinity, light, temperature, and nutrient concentration upon seagrass species distribution and productivity, population growth, and succession by conducting controlled factorial laboratory and field/mesocosm experiments. Light compensation points and limiting nutrient dynamics need to be determined for growth in the carbonaceous (and high-sulfide) sediments of Florida Bay. The effects of persistently reduced light on seagrass species distribution need to be assessed.

iii. Conduct surveys of benthic and epiphytic macroalgae to assess relative eutrophication of the system and possible competitive effects upon the seagrasses.

iv. Determine the age structure and mortality and reproduction patterns in Thalassia, Halodule, and Ruppia subpopulations. The distribution of Thalassia rhizomes in areas currently unvegetated or vegetated by other seagrasses should be used to map past mortality events.

v. Monitor productivity, plastochrone interval, and shoot-specific leaf area in Thalassia; these characteristics provide indications of physiological status of Thalassia and are indicative of environmental stress. Determine whether these characteristics are useful indicators in the other seagrass species.

vi. Determine the etiology of seagrass die-off in situ in Florida Bay. The patchy distribution patterns, density dependence, spread rates, and leaf necroses associated with die-off of Thalassia suggest the involvement of a pathogenic organism. Given the high concentrations of dissolved sulfide in sediment porewater, hypoxic stress of subterranean Thalassia tissue also may play a role. Although it may be impossible to determine with any certainty what precipitated the original die-off event, it is still important to determine the proximal causes of die-off if we are to anticipate future events.

vii. Determine the influence that increased epiphytism, decreased water clarity due to resuspension of unvegetated sediments, and increased phytoplankton concentrations have upon seagrass recolonization and population recovery rates.

viii. Develop spatially coupled physical-biological models linking experimentally verified causes of die-off to the distribution of seagrasses throughout Florida Bay in order to evaluate recovery potential and predict the effects of restoration efforts. Verify these models through a continuing monitoring program.

2. What environmental factors explain the pattern of mangrove die-back within the Florida Bay ecosystem?

Mangrove communities in South Florida are potentially affected by a number of anthropogenic and natural factors whose relative significances are not well known. These may act synergistically to significantly change the mangrove community. The importance of the transition zone and island mangrove communities to the Bay ecosystem dictates that greater attention be paid to their physiological ecology, growth, and reproductive biology.

Hurricane Andrew severely damaged more than 70,000 acres of mature mangrove forest on the west coast of Everglades National Park. Winter freezes in 1983 and 1989 also damaged large areas of mainland mangrove communities, but no quantitative damage assessment has been made. Reduction in freshwater delivery to the southern margin of the mainland and Florida Bay also has been suggested as a factor in mangrove mortality. An increasing problem is associated with the exotic tree Schinus terebinthifolius, which has displaced mangroves in some areas of the Gulf coast mangrove forest.

The impact of the 1989 freeze may have been exacerbated by low water levels in the Everglades, which in turn resulted from drought and hydroperiod manipulations. Although hurricanes have been an historical factor in the evolution of South Florida mangrove ecosystems, dispersal and establishment of alien plant species in mangrove communities is facilitated by hurricanes. Mangrove communities, possibly more than any other community, will be vulnerable to changes in tidal inundation patterns associated with eustatic sea-level rise and the accelerated sea-level rise forecast in global-climate-change scenarios.

Key Research Needs

A combination of monitoring and experimentation will be required to elucidate the key mechanisms that could change the mangrove communities of Florida Bay, the extent of present mortality, and the impact of this upon the Bay ecosystem.

Specific Tasks

i. Monitor mangrove community composition and coverage on the South Florida mainland and islands in Florida Bay. Quantify changes for the entire area on a multi-year schedule, and sample smaller areas more frequently. Analyze available aerial photographs to determine past changes. Incorporate all data into a GIS database.

ii. Determine the effects of tidal inundation patterns, freshwater-flow alteration, and nutrient availability upon mangrove growth, physiology, and reproduction.

iii. Determine the relationship of past, present, and future freshwater-flow patterns to the extent, vigor, and functional integrity of mangrove communities within the mainland region of Everglades National Park and on the Florida Bay keys.

iv. Continue assessment of Hurricane Andrew's impacts on mangroves, with particular emphasis on recovery patterns and invasion by exotic plant species.

v. Model mangrove population dynamics in Florida Bay and adjacent mainland areas based upon the above data [i-iv].

vi. Determine the significance of mangrove habitats, production, and nutrient cycling to the Florida Bay ecosystem by studying food-web and habitat utilization, and incorporate the mangrove community into an overall ecosystem model (see section B).

vii. Monitor salinity of hypersaline ground vater on islands in relation to mangrove dieoff.

3. What has been the cause and consequence of sponge die-off and the subsequent alteration of hardbottom communities?

Mass mortality of sponges has occurred throughout large areas of the south-central and southwestern portions of Florida Bay. Circumstantial evidence links sponge mortality to the presence of the algal bloom that has persisted in that region; however, no experimental confirmation of that linkage exists. Sponges are a major structural component of Florida Bay hardbottom communities and may contribute to water clarity through filtration. Little is known about the ecological implications of their loss.

Specific Tasks

i. Determine the mechanism for sponge mortality. Experimentally verify the linkage between phytoplankton blooms and sponge mortality using cultures of dominant bloom species in controlled laboratory experiments. Transplant sponges to bloom areas to evaluate susceptibility of individual species. Include cellular analysis of sponges.

ii. Incorporate hardbottom communities into a biological monitoring program. The initial goals of such a program will be to evaluate variations in abundance of the structural components of hardbottom habitat across Florida Bay and use these data to experimentally test the effects of change in this community and the community's relationship to living resources.

D. Living Resources

The living resources of the Bay include, as a general category, those organisms specially recognized because of the species' ecological, regulatory, conservation, and/or economic value. To varying degrees, many of these have exhibited population trends suggesting that Florida Bay's capacity to support them is declining. Other species, however, have not been studied enough to evaluate trends

1. Has recruitment into Florida Bay been affected by habitat changes in Florida Bay, and have altered environmental conditions affected growth and survival of animals in Florida Bay?

The interactions of known and suspected environmental changes such as salinity variations, current modifications, nutrient or pollution inputs, freshwater input, algal blooms, grass die-offs, and sponge die-offs are suspected to affect the distribution and abundance of living resources. A given taxon's sensitivity to any of these factors may differ with life history, trophic position, and length of exposure to Florida Bay water (e.g., whether the entire life cycle or just a part is spent within Florida Bay). Often the most sensitive stages are the recruit and the juvenile stages. Therefore, the study of recruits and juveniles can provide valuable predictive information about subsequent overall population changes. Along with community-level studies, a suite of critical or indicator species will be selected as the focus of these population level and physiological studies.

Key research needs

A combination of monitoring, research, and modeling is required to link habitat change to shifts in living resources. The key elements of each are defined below.

Specific Tasks

i. Develop a baywide faunal monitoring program in the major sub-environments of the Bay. Design surveys to establish correlations with other measured factors that then will be tested experimentally for causal relationships. Compare results with past studies in retrospective analyses. Critical observations should include but not be limited to the following:

- the age and/or size of animals - e.g., detection of shifts in abundance from one size- or age-class to another will lead to the testing of hypotheses relating population changes to ecosystem changes.

- health and condition of organisms.

- reproductive condition or stage.

Additional actions needed to test specific hypotheses may include sampling algal blooms within and beyond Florida Bay and sampling across gradients of salinity, latitude, and distance from channels between the keys.

The monitoring program must be of sufficient duration to permit meaningful timeseries analyses of trends and restoration efforts. Special attention is needed on the following taxa:

- Pink and Caridean Shrimp - because of their utilization of grassbeds as a nursery area.

- Spiny Lobster - because algal blooms depleted the number of sponge shelters for juvenile lobster.

- Fishes - because they may be quantitatively censused with nets in bloom waters. Community-level analyses of fish assemblages may provide a means to measure changes in habitat.

- Mollusks - because many are indicative of salinity and because shell accumulations permit comparisons of compositional change over time.

ii. Conduct comprehensive life-history studies of selected species for basic information such as levels of recruitment and transport of recruits, critical shelter and forage habitats, and how habitat use changes with environmental modification.

iii. Conduct manipulative field experiments testing the impacts of change in critical habitats on distribution, abundance, and survival of critical life stages.

iv. Couple the above field work with laboratory-based physiological and behavioral experiments investigating the tolerances and preferences of fishes to conditions that exist in Florida Bay or might exist under proposed management strategies.

v. Develop models linking experimental data to information on life histories, habitat change, and changes in the physical environment that will emerge from research described in other areas of this plan. These models should be sufficiently detailed to evaluate causes of changing abundance patterns, if any, and sufficiently broad to evaluate any changes that occur on a regional scale. Model outputs need to be regularly verified by the monitoring and experimental approaches described above.

2. Has habitat degradation or loss caused a reduction in fishery productivity in the Bay?

Degradation of Bay habitats has been blamed for causing declines in fishery resources as reflected in fishery-dependent data. However, these data encompass only adult life-history stages. Although these data are sufficient indicators of fisheries productivity at a given time, they are subject to biases due to gear type, angler behavior, and fishing regulations. Furthermore, the fact that commercial fishing has been prohibited in the NPS portion of the Bay since 1985 further confounds data interpretation. In short, the causes of observed declines have

not been identified with any certainty. Some fishery-independent sampling has been conducted in the Bay and adjacent waters but only to a limited areal and temporal extent. Collectively these data may provide some basis for comparison with results from future surveys.

Key Research Needs

Detailed information is needed on the quality and quantity of available habitat and species' habitat preferences. Much of this information will be obtained from research and monitoring efforts described earlier. Fisheries landings data, collected since the 1960's, will provide an initial basis for research on impacts upon fisheries productivity and can guide additional data collection allowing more rigorous determination of cause and effect relationships. The direct impact of habitat change or degradation can be ascertained by analyzing specific tissues and forage items that accumulate toxins and pollutants. Elucidating the physiological impact on selected species of such toxins will require laboratory studies.

Specific Tasks

i. Collect unbiased information on all the life-history stages of selected indicator species. This information is best derived by supplementing fishery- dependent sampling with fishery-independent sampling. Fishery-independent sampling should be directed at specific life-history stages and should be habitat based.

ii. Focus on habitat-based research, particularly the structure and function of each habitat type. Research that defines the linkage between seagrass and mangrove habitats and the effects on fisheries of changing benthic vegetation is critical. Specifically, pre- and post-die-off seagrass and mangrove faunal community composition must be quantified.

iii. To address the decline in the pink shrimp fishery, develop a model that relates cohorts on nursery grounds to cohorts in the Tortugas fishery landings.

iv. Attempt to measure the impacts of habitat change via tissue analysis and stomach contents analyses. For some species, tissues will need to be examined to define the overall health of a particular species within the Bay.

v. Conduct complementary laboratory physiological research on early life- history stages of key species to evaluate changes in habitat on coastal resources.

3. Have environmental and habitat changes in the Bay affected the distribution and reproductive success of upper-trophic-level consumers?

Everglades National Park and Florida Bay are important foraging and rookery habitats for many species of wading birds, shore birds, and top-level predatory birds such as eagles, ospreys, and brown pelicans. In addition, the entire U.S. population of the Great White Heron resides in southern Florida, and about 65% of the population nests on fringing mangroves and mangrove islands in Florida Bay. Declines in many species, particularly wading birds and ospreys, have been measured over the past several years. One possible explanation for these population declines is that they are the direct result of declines in the quality of resources available.

Four species of marine turtles have been reported to occur in Florida Bay; loggerhead and green turtles are regular residents. Kemp's ridley and the hawksbill turtle are present but less common. Adult male loggerheads are particularly common, and the Bay may serve as adult resident habitat or an important migratory route for the western Atlantic loggerhead reproductive contingent. Seagrass communities provide forage for turtles, and seagrass community diversity has been shown to be significant in providing sufficient nutrition for the herbivorous green turtle. Fibropapilloma disease affects 70% of all captured green turtles and has been documented in more loggerheads within South Florida than ever reported from any other geographic location. Although the etiology of the fibropapilloma disease is unknown, one hypothesis is that environmental contaminants may weaken the turtle's immune system.

Bottlenosed dolphin are regular residents and users of Florida Bay. Although dolphins consume Bay finfish, the relative importance of this habitat to dolphins in the southeastern U.S. is unknown.

Manatees utilize the Bay and adjacent waters on a seasonal basis and their numbers within the Bay have been well documented. Changes in the distribution of manatees in the Bay over time suggest a decline in use of the northern Bay, although historically, the northeastern portion was the most important area of the Bay for manatees. Proposed changes in freshwater inflow may have direct impacts on the benthic vegetation, which is critical forage for manatees. How these changes in vegetation have affected the distribution and abundance of manatees in the Bay is poorly understood.

The endangered American crocodile is found exclusively in South Florida from the southern portion of Biscayne Bay to Florida Bay. The distribution and growth of crocodiles are related to seasonal fluctuations in salinity. In addition, the survival of hatchlings has been linked to periodic access to freshwater. How changes in freshwater inflow affect the distribution, abundance, and survivorship of hatchlings is unknown.

Clearly, changes in freshwater inflow into the Bay will influence the quality and quantity of habitat available to all life-history stages of manatees, turtles, dolphins, and crocodiles. The scientific basis for predicting the extent of the habitat change is currently weak. However, as coastal habitat outside the Bay diminishes in quality and quantity, the relative importance of the Bay to the protection and recovery of these species will likely increase. Therefore, investigation of the impacts of habitat change in the Bay upon all protected species groups is imperative.

Key Research Needs

Protected areas such as the Bay will likely become increasingly important as refuges for protected species as coastal development continues. To develop predictive models, information on the abundance and distribution of animals in the Bay is critical. These results will be used to evaluate the carrying capacity of the Bay for these species, an essential element of restoration management. Information on the movements and use of the Bay as nursery or developmental habitat is essential. Information needs to be collected over many years to delineate population trends in the species that have long generation times. Information on the impact of toxins and pollutants on protected species is critical if recovery is to be achieved.

For some species, such as osprey and bald eagle, available monitoring records are sufficient to determine the current status of populations in the Bay; for others, however, regular population monitoring should be initiated and continued. For all species, consistent censusing must be either continued or initiated to determine the impacts of habitat change on these populations. Monitoring of both the nesting and foraging components of all populations are needed. As such, all species can be used as indicators of ecosystem health. The accumulation of toxins has been documented for some species. The impact of this on individuals and on reproductive and hatchling success must be quantified.

Specific Tasks

For predatory birds:

i. Monitor the abundance and distribution of key species. The most commonly used method is via aerial survey counts. To evaluate hatching and fledging rates, nests must be routinely sampled.

ii. Determine the relative importance of specific areas for nesting, feeding and roosting within the Park and the Bay, using radio- and satellite-tracking tags.

iii. Analyze stomach contents to provide needed information on feeding and habitat preferences.

iv. Sample nests for egg and hatchling productivity.

v. Population changes can only be determined by monitoring these species in the Bay and adjacent coastal waters. On the larger scale, aerial surveys are an appropriate method to census animals and evaluate distributional changes.

For crocodiles:

vi. Nest censuses need to be used to determine population status.

For sea turtles:

vii. Netting studies are appropriate when accompanied by tagging as currently practiced. The use of point-transect sampling may also provide abundance estimates.

viii. Distribution and abundance data on legally protected species, Florida Bay habitat characterization and environmental parameter data need to be integrated in order to evaluate the effects of environmental changes on turtles.

ix. Radio-tagging studies should be undertaken to provide information on the movements of animals within and outside the Bay, including their migratory movements.

x. The examination of stranded animals should be used to provide additional information on habitat use and preference via stomach-contents analyses. Stomach contents should be examined via gastric la ~age of living animals.

xi. Specific study of the fibropapilloma disease is needed to provide for mitigation and recovery.

For all species:

xii. Analyses of toxins in forage items and tissues must be completed and tissues from all life-history stages should be analyzed for contaminants.

VI. REFERENCES

1. Interagency Agreement on South Florida Ecosystem Restoration. September 23, 1993.

2. Federal Objectives for South Florida Restoration. Prepared by the Science Sub-group of the South Florida Management and Coordination Working Group, Nov. 15, 1993.

3. M.B. Robblee, T.V. Armentano and R.W. Snow. A Research Program for Restoration of Florida Bay, May 18, 1993.

4. P.B. Ortner, D.E. Hoss and J.A. Browder (eds.). NOAA Workshop on the Restoration of Florida Bay, July 14-16, 1993. Conveners: B.Brown and P.B.Ortner.

5. D.F. Boesch, N.E. Armstrong, C.F. D'Elia, N.G. Maynard, H.W. Paerl and S. Williams. Deterioration of the Florida Bay Ecosystem: An Evaluation of the Scientific Evidence, September 15, 1993.

6. A copy of the full official policy statement is available from the U.S. Global Change Research Program, National Science Foundation.

7. Bulletin of Marine Science, Vol.44(1): Symposium on Florida Bay, a Subtropical Lagoon, U.S. National Park Service/Everglades National Park and University of Miami/Rosenstiel School of Marine and Atmospheric Science, 1-5 June 1987, 524pp.

8. Surface Water Improvement and Management Plan for the Everglades: Supporting Information Document (472 pp) and Appendices. South Florida Water Management District, March 13, 1992.

9. Federal Objectives for South Florida Restoration by the Science Sub-Group of the South Florida Management and Coordination Working Group, Nov. 15, 1993.

SUBREGION 9:

LOWER EAST COAST URBAN AREA

INTRODUCTION

Subregion 9, the LEC Urban Area, extends about 160 km (100 mi) from West Palm Beach to Florida City (Figure 1). It encompasses those portions of Dade, Broward, and south and central Palm Beach counties that lie east of the WCAs and the East Everglades area bordering ENP. The area is primarily urban, forming a megalopolis that stretches almost the entire length of the subregion, but it also contains substantial agricultural acreage, particularly in southwestern Dade County. Both urban and agricultural areas receive benefits from what natural systems remain in the subregion, including oxygen production, detoxification and dispersion of pollutants, nutrient recycling, fish and wildlife production, outdoor recreation, and tourism attractions (McPherson et al. 1976).

The LEC's demands for water, energy, recreation, housing, and other services have considerable impact on other subregions of South Florida. The LEC is tied to these other subregions principally by water. Groundwater, dependent partly on recharge by canals extending from Lake Okeechobee, is the major water source for the urban areas. Dade County groundwater, in turn, is the primary source of drinking water for the Florida Keys. Releases from the regional system help prevent saltwater intrusion along the coast. These demands affect the water needs of the lake and those areas connected to the lake by the St. Lucie Canal and Caloosahatchee River. Water needs, drainage demands, and associated runoff quality of the agricultural area in western and southern Dade County impact the water supply to ENP and Florida Bay. Subregion 9 is on the downstream receiving end of many surface water discharges from other subregions. Florida Bay, Biscayne Bay, and the north Florida Keys receive discharges from the LEC. Residents of Subregion 9 and tourists alike benefit from the wildlife resources and recreational values of surrounding subregions, especially those near the metropolitan area. The LEC's proximity to three National parks (BNP, ENP, and Dry Tortugas) and a National preserve (BCNP), in addition to the Florida Keys, reefs, and WCAs, makes it a magnet for ecotourism (Ferrell 1993). The recognized tourism values of these nearby areas enhance the image and economy of the LEC and are a primary reason many people travel to or through Subregion 9. In addition, fishery resources of the natural areas and products of the agricultural areas provide food for the LEC and beyond.

BACKGROUND

Description of the Natural Area

The LEC has many types of topographic features that provide varied habitats. These include: coastal barrier islands with beaches and dunes (the southernmost sand barrier islands of the U.S. East Coast); an extensive estuarine lagoon between the islands and mainland; a narrow coastal plain occupied in part by shoreline mangroves; a linear ridge of higher land, now almost fully urbanized, with fragmented remnants of natural areas; interior short-hydroperiod wetlands, many of which have been drained; a few natural inland lakes, now much reduced in size; many artificial rockpit lakes and retention/detention ponds; a natural offshore reef tract plus numerous artificial reefs; and an extensive system of man-made freshwater canals, which has totally replaced natural tributary drainage.

The outstanding topographic feature of Subregion 9 is the Atlantic Coastal Ridge, a narrow limestone ridge that borders the Atlantic Ocean and forms a barrier between the ocean and the Everglades basin. The ridge is about 3-16 km (2-10 mi) wide and has an average height of about 2.4 m (8 ft) above mean sea level. Cities initially developed along the ridge; now they extend far beyond it. North of Fort Lauderdale the bedrock is sandy limestone and is covered with a deep sand mantle of old dunes that form ridges and elongated depressions. South of Fort Lauderdale the bedrock is Miami oolite covered with little or no sand. The surface south of Coconut Grove essentially bare rock, and this portion is often called the Miami Rock Ridge. Among numerous outcrops of the formation, one of the most prominent is Silver Bluff, visible in Coconut Grove bordering Biscayne Bay, where the

ridge reaches its maximum height of 7.3 m (24 ft) above sea level and maximum thickness of 10.4 m (34 ft). At its south end, the Atlantic Coastal Ridge swings southwest, then west, and disappears in ENP, about 35 km (22 mi) west of Homestead (Craig 1991; Brown and Parker 1945; Davis 1943; Harper 1927; Hoffmeister et al. 1967; Parker et al. 1955; Snyder et al. 1990). Another unique natural formation is a reef on the northeast shore of Key Biscayne, composed of fossilized roots and pneumatophores of black mangrove, estimated at 1000-2000 years old, which may be the only one of its kind in the world (Hoffmeister and Multer 1965).

The Atlantic Coastal Ridge was historically covered with pines and palmetto, interspersed with hardwood hammocks. It was reported in 1906 that a band of timber 3-13 km (2-8 mi) wide extended along the coast. At that time, many small towns existed along the Florida East Coast Railway between Palm Beach and Miami, but there were no settlements more than 3 km (2 mi) west of the railroad, where the Everglades were described as presenting an unbroken front extending more than 96 km (60 mi) (U.S. Senate 1911).

The Atlantic Coastal Ridge is breached in many places in Dade and Broward Counties by shallow sloughs, known as transverse glades. Historically, many of these contained streams and rivers, which drained water from the Everglades and fell in shallow rapids through the limestone ridge. Streams that occurred in Subregion 9 were, from north to south, Hillsboro River, Cypress Creek, New River, Snake Creek, Arch Creek, Little River, and Miami River. Frequently in the dry season, runoff disappeared into fissures in the limestone. In 1847, it was reported running water could often be heard and seen 1.8-2.4 m (6-8 ft) below the surface in pine woods between the Everglades and Biscayne Bay. In 1913 springs of considerable size were still seen along the rock ridges of the pinelands. Fresh water also emerged in many perennial springs at the base of the ridge along the shoreline of Biscayne Bay and even from the bay bottom. This natural system is now completely converted to an extensive system of drainage canals, which began in the New River basin in 1907 and in the Miami River in 1909. The largest of these are the West Palm Beach, Hillsboro, North New River, and Miami canals (Brown and Parker 1945; Davis 1943; Harper 1927; Hoffmeister et al. 1967; Klein et al. 1975; Parker et al. 1955; Teets et al. 1991; U.S. Senate 1911). Alignment of several major canals follows the natural drainages of transverse glades through the ridge (Leach et al. 1972). Cypress Creek Canal in Pompano Beach, Broward County, historically was a unique cypress slough forming one of the glades (Moran 1979). Hydrologic changes caused by canal drainage and lowered water table resulted in dramatic changes in plant communities, especially disappearance of marshes (e.g., around Clear Lake and Lake Osborne in Palm Beach County) and wet prairies (Austin 1976; Austin et al. 1977; Richardson 1977). Most wet prairies immediately west of the Coastal Ridge were destroyed between 1943 and 1970, including 80% of those in Broward and Palm Beach counties (Birnhak and Crowder 1974). Only scattered remnants of cypress forest wetlands are still present in urban north Broward; some of these are preserved as parkland (Broward Bd. Commiss. 1989b). In South Dade County, what is now the lower C-111 basin received most of its runoff from the southern portion of the Coastal Ridge, and these surface and groundwater flows comprised the primary source of freshwater inflow to northeastern Florida Bay. Now, with urban development of the ridge and operation of the C-111, much of the natural runoff is diverted by canal to Biscayne Bay (COE 1994).

Even with extensive, intensive development, the LEC still contains many representatives of most natural plant communities characteristic of South Florida, although they are now reduced, fragmented, and stressed. These include beach and dune; mangrove swamp; coastal saltwater marsh; freshwater marsh; maritime hammock; coastal strand; rockland hammock; pine rocklands; scrub; sandy pine flatwoods; and short-hydroperiod wet prairie. Some of these communities, as well as many individual plant species within them, are endemic only to South Florida and are protected in parks in the three counties.

The subtropical pinelands on the Miami Rock Ridge are monospecific stands of South Florida slash pine with a diverse understory of palms, shrubby hardwoods, and herbs (Snyder 1986). Dade County probably has more endemic plant taxa (55-65) than any other Florida county, and most of these occur in pine rocklands (Garvue 1994; Muller et al. 1989). In fact, the pine rocklands contain the third largest concentration of endemic native plants in the continental U.S. (Dade DERM 1994b). Of 186 native species recorded during a pineland inventory, 67 were considered exclusive to South Florida pinelands (Loope et al. 1979). Estimates of the extent of pineland that formerly existed on the ridge range from 162,000-185,000 acres (Doren et al. 1993; Gleason 1984; Loope et al. 1979). Because pine rocklands were high and dry throughout the year, they were - and still are - prime targets for farmers and developers (Cox et al. 1994; Dade PRD 1994b; Snyder et al. 1990). Only 4400 acres of pineland remained in Dade County; just over half is in private ownership and not protected in parks. Many small remnants

have been invaded by Brazilian pepper (*Schinus terebinthifolius*) or are otherwise degraded (Doren et al. 1993; Loope et al. 1979). Only a few areas outside ENP are likely to be preserved (Snyder 1986). These include a few areas of considerable acreage managed by Dade County and some owned by the Federal government. Federal agencies control about 440 acres, most in the Richmond Pine Rocklands; this forest accounts for more than one-third of all publicly owned pine rocklands in Dade County (Maguire 1995).

Hammocks, dense forests with many species of tropical origin, are considered the climax vegetation of South Florida (Alexander 1967a; Alexander and Crook 1984; Davis 1943; Snyder et al. 1990). Of 128 species found in a rockland hammock southwest of Miami, 5% were endemic to South Florida, while 82% were also found in the West Indies. South Florida was the only location in the U.S. for 62% of the species (Phillips 1940). Boynton Beach Hammock had 85% tropical composition (Austin and Weise 1972); Pompano Beach Hammock had 87% (Alexander 1958). Historically, more than 500 hammocks (oak-palm or tropical hardwood) were scattered along the Coastal Ridge northward into Brevard County (Gleason 1984; Richardson 1977). The largest hammock was Brickell Hammock along Biscayne Bay below Miami (Harper 1927). Hammocks occurred on the ridge wherever flowing water had carved caverns, sinks, or channels (Craighead 1984; Taylor 1991; Thorhaug et al. 1976). They exist now in only scattered remnants. A previously undocumented tropical hardwood, about an acre in size, was found in 1992 on Key Biscayne, on a mound hidden in mangroves (Huck 1995). Into the 1970s, the half-mile-long Boynton Beach Hammock was the last coastal hammock of its size north of the Keys (Austin and Weise 1972; Richardson 1977). Hammocks near the coast are now stressed by lowered water tables (Alexander and Crook 1984).

Scrub habitat historically occurred along the Coastal Ridge in a narrow strip along the mainland eastern shore south to northern Dade County, throughout a topographically complex series of parallel ridges and swales (Austin et al. 1977, 1987; Davis 1943; Harper 1927; Lovestrand 1990; Richardson 1977; Steinberg 1980). Swamps and marshes were common in depressions cut through the scrub ridges. The largest scrub ridge in Broward County was traversed on the north by the Hillsboro River and on the south by Cypress Creek (Steinberg 1980). Remnants exist in portions of Subregion 9 north of Fort Lauderdale, in isolated sites surrounded by urban development. (Broward PRD undated(a); City of Boca Raton 1991; Davis 1943; Austin et al. 1987; Fernald 1989; Palm Beach DERM undated). Most scrub in Palm Beach County has been destroyed (Birnhak and Crowder 1974; Fernald 1989).

South and southeast of the Coastal Ridge in Dade County, just inland of the mangrove band and merging with Subregion 8, is a broad, marl-forming, short-hydroperiod coastal prairie that extends from Silver Bluff south around the tip of the ridge and forms part of the "southeast saline Everglades" (Egler 1952; Harper 1927). The area was described historically as an endless sawgrass prairie dotted with dense tree hammocks, which supported large populations of wildlife, especially larger birds (Egler 1952; Small 1918 as referenced in Alexander and Crook 1973). The area's characteristics have been determined by a variety of interacting factors, including groundwater seepage from the ridge (Gleason and Spackman 1974), tidal flooding, sporadic saltwater flooding from hurricanes, lowered water table, sea-level rise, fire, exotic plant invasion, and canal and road construction (Alexander 1967b; Egler 1952). Construction of the U.S. 1 embankment by the FECR cut off about 38% of overland water flow and created a more saline condition east of the roadbed, where mangroves have become established well inland (FHWA/FDOT 1992). Much of the area was cleared for vegetable farming; ditching and dredging canals to make land suitable for cultivation was reported in 1918 (Alexander and Crook 1973; Small 1918 as referenced in Alexander and Crook 1973). Alexander and Crook (1973, 1975) conducted an extensive evaluation of vegetation changes between 1940 and the early 1970s. A new survey to document and interpret changes in this area is currently underway (Ross et al. 1994). Almost 80,000 acres of this prairie are now in public ownership or under acquisition (FHWA/FDOT 1992; Young 1994, 1995). Included are more than 13,000 acres of FPL property that will be used as a mitigation bank and restored to more natural conditions (Cotleur Hearing 1995).

An estuarine system, through which the AIW runs, separates the coastal barrier islands from the mainland. The most prominent estuaries are Lake Worth and Biscayne Bay. Lake Worth is considered part of Subregion 3 (Upper East Coast). South Biscayne Bay, included in BNP, is included in Subregion 8 (Southern Coastal Areas). The estuaries discussed in Subregion 9 are West Lake in Broward County and the north and central portions of Biscayne Bay in Dade County.

West Lake is a 1400-acre coastal wetland and mangrove preserve that extends for 5 km (3 mi) along the AIW in Hollywood. Although surrounded by dense residential and industrial development, West Lake is the best example of the mangrove community remaining in Broward County and largest of its kind between West Palm Beach and Miami. It is also one of the largest mitigation projects ever conducted in Florida. The 1985 purchase agreement included almost 200 acres of wetland creation. West Lake is an important nursery area for fish, especially snook ((Broward Bd. Commiss. 1989b; BCPC 1989a; Broward PRD 1989; MacAdam 1990; G. MacAdam, pers. comm.). This preserve is one of six sites being evaluated by the Florida Greenways Commission regarding critical aspects of creating successful local greenways (Fl. Greenways Comm. 1994). Another Broward mangrove preserve is located at Port Everglades at the mouth of the FPL cooling canal (Broward Bd. Commiss. 1989b).

Biscayne Bay is a subtropical lagoon about 64 km (40 mi) long that extends the length of Dade County (Evoy and Schechtman 1986), making it a dominant feature of the county. It covers 1108 km2 (428 mi2) and has a watershed of 2429 km2 (938 mi2) (SFWMD 1995). The bay has been the subject of extensive study; a recent Biscayne Bay bibliography contains over 1700 citations (Hale 1993). Biscayne Bay is technically classified as a shallow, tidal bar-built estuary (Hela et al. 1957). North Biscayne Bay (north of Rickenbacker Causeway) is hydrographically complex because of massive dredge and fill activities and the presence of several causeways and many islands (most artificial) that alter circulation (Hela et al. 1957; Roessler and Beardsley 1975; Thorhaug et al. 1976; Wanless 1976). Since 1900, 49% of the submerged area of North Biscayne Bay has been permanently altered by dredging and filling and construction of more than 145 km (90 mi) of bulkheaded shoreline, artificial islands and causeways, channels, and cuts to the ocean (Alleman et al. 1995a,b; Evoy and Schechtman 1986). Several relatively small tributaries enter the North and Central Bays. Flow of the Miami River is greater than the others entering North Bay combined but is insignificant compared to tidal flow through the bay (Hela et al. 1957; Michel 1976); discharge from the river is rapidly exchanged with coastal waters through Government Cut and Norris Cut inlets (Lee and Rooth 1976).

The altered hydrological system has increased point-source discharge (Thorhaug et al. 1976); the canal system and Miami River are principal routes for pollutant runoff (Waite 1976). Until 1956 when a sewage treatment plant began operation, the Miami River was essentially an open sewer discharging untreated waste directly into the bay (City of Miami 1992; Dade DERM 1993b; Hela et al. 1957). Inland waters of the LEC were still considered seriously polluted in the early 1970s, primarily because of inadequately treated sewage (DOI 1973; FWQA 1970; Klein et al. 1975; Lynch et al. 1976; Teets et al. 1991). Even now it is not unusual for portions of Biscayne Bay to be closed to swimming and fishing because of high bacteria levels resulting from breaks in outmoded sewer pipes (Miami Herald 1995a, 1995b; Stone and Suman 1995). Water quality of the Miami River is still adversely affected by sewage effluent and by agricultural and urban runoff (City of Miami 1992; Dade DERM 1993b; Gulf Engineers 1993; Irwin undated). Arch Creek, a tributary to North Bay, has high levels of ammonia and coliform bacteria, significant amounts of metals in sediments, and high levels of phthalates in tributaries (Alleman et al. 1995a,b; Dade DERM undated(a),(h)). The most significant pollution problem in North Bay is leachate from the Munisport Landfill, a Superfund site placed on the National Priorities List in 1983 due to migration of leachate-contaminated groundwater into a State mangrove preserve (EPA 1990c, 1994b,c).

The shoreline of Biscayne Bay historically was lined by mangroves. Most shoreline vegetation has been altered by development and other anthropogenic impacts, including loss of freshwater flow, ditching and subsequent increase in salinity, land clearing, dredge and fill projects, construction of seawalls, and erosion by boat wakes (Huck 1995; Odum et al. 1982; Reark 1975; Teas 1977; Teas et al. 1976). Today substantial stands of mangroves exist at only a few sites, primarily on the mainland south of Coral Gables, west shore of Virginia Key, northwest shore of Key Biscayne, and Oleta River SRA. Alterations in hydrology (i.e., mosquito ditches, agricultural ditches) and the resulting increase in salinity, along with sea-level rise, have allowed mangroves to expand inland beyond the coastal band. This has resulted in a scrub mangrove community growing on former freshwater marl marshlands that were salinized as a consequence of drainage. These mangroves show overt signs of stress and probably suffer nutrient deficiencies (Alexander and Crook 1973; Ball 1980; City of Miami 1987; Egler 1952; Reark 1975; Teas 1976).

The bottom of South Biscayne Bay is dominated by turtle grass (*Thalassia testudinum*), but in portions of the bay most impacted by urban development turtle grass has generally disappeared, primarily because of turbidity. One extensive seagrass area remaining in North Bay is north of the Julia Tuttle Causeway. This is probably the most

biologically diverse and productive area in the bay and rivals any community sampled in South Bay. Much work has been done on techniques for replanting and restoring seagrass in denuded areas, especially North Biscayne Bay (Evoy and Schechtman 1986; Thorhaug 1976; Thorhaug et al. 1976). Restoration of bay seagrass beds and mangrove shorelines improves habitat for invertebrates (Voss 1976) and also provides habitat for fish. Studies in Biscayne Bay showed the most important determinant in abundance of juvenile fish was density of seagrass (Evoy and Schechtman 1986). Mangrove planting techniques have been developed, and since the early 1980s replanting of mangroves and seagrass has been required as mitigation for construction projects (Alleman undated; Evoy and Schechtman 1986; Teas 1977).

In 1974 the Florida Legislature established the Biscayne Bay Aquatic Preserve, which includes all publicly owned islands and all submerged lands between Sunny Isles Causeway (State Road 826) on the north and Card Sound Road (State Road 905A) in Monroe County on the south, excluding BNP. It also includes lower portions of most tributaries. Funds provided pursuant to this Act have been the main support for bay management programs (Evoy and Schechtman 1986). The 400 acres of shallow tidal flats and mangrove forests on the west side of Virginia Key have been designated as a Critical Wildlife Area by the FGFWFC (undated). At least 512 species of temperate and tropical fish have been recorded from Biscayne Bay (de Sylva 1976). Saltwater fish species, such as tarpon, are often found far upstream in canal and river systems (Davis 1943; Kushlan and Lodge 1974). The bay supports commercial and recreational fisheries; pink shrimp, harvested in a baitfish fishery, is the most important species harvested by weight (Evoy and Schechtman 1986).

Population

The LEC is the most heavily urbanized area of not only South Florida but the entire State. With a combined population of more than 4 million people, the three counties of Subregion 9 are home to more than 30% of Florida residents. Dade, Broward, and Palm Beach counties are 1, 2, and 3 respectively in the State's population rankings. Dade County itself comprises almost 15% of Florida's population (Bur. Econ. Bus. Res. 1994). The area was first opened to rapid growth and promotion of tourism when the FECR was completed to West Palm Beach in 1894 and to Miami in 1896 (Nicholas 1974), followed closely by the start of massive drainage efforts in the first decade of the 1900s (Klein et al. 1975; U.S. Senate 1911). These drainage programs developed for land reclamation, flood control, and water management enabled urbanization of the LEC (Leach et al. 1972).

Water Supply

Water availability in Subregion 9 depends on rainfall and storage capacity in surface and groundwater systems. The LEC is a producer, as well as South Florida's largest consumer, of fresh water. Florida's heaviest rainfall occurs along the Atlantic Coastal Ridge between Boynton Beach and Miami, where the annual average is as high as 64 inches (1975 data). Rainfall decreases inland and is only 52 inches over Lake Okeechobee (Davis 1943; Klein et al. 1975; McPherson et al. 1976)

The LEC is dependent on shallow, unconfined surficial aquifers for urban and agricultural fresh water. Broward and Dade counties rely entirely on groundwater; groundwater accounts for 80-90% of Palm Beach County's potable water. Most groundwater (100% in Dade, 90% in Broward, 85% in Palm Beach) is pumped from depths of less than 46 m (150 ft); many wells are much shallower (Alvarez and Bacon 1988; Rodis and Land 1976). The Biscayne Aquifer, the largest and most productive unit of the surficial system, is one of the area's most valuable natural resources. It underlies an area of about 7770 km^2 (3000 mi^2), including all of Dade County and most of ENP, all of Broward County, and part of south Palm Beach County. The aquifer is composed of sandy limestone and calcareous sandstone with many solution holes and cavities. It is one of the most permeable aquifers ever investigated and probably the most permeable water-table aquifer in the world (Brown and Parker 1945; Kreitman and Wedderburn 1984; Parker et al. 1955; SFWMD 1994a; Schroeder et al. 1958; Walters 1987). Aquifer recharge is mainly by direct infiltration from rainfall, supplemented by water carried into the area by canals to supply wellfields and prevent coastal saltwater intrusion during the dry season. Discharge is by direct evaporation, evapotranspiration after infiltration, canal drainage, coastal seepage, and pumping for utilization by man (Haire and Shaw 1989; Klein et al. 1975; Klein and Hull 1978; SFWMD 1992, 1993, 1994a; Shine et al. 1989).

The Biscayne Aquifer was designated a sole-source aquifer for Dade and Broward counties in 1979 by the EPA under the Safe Drinking Water Act. It is also the primary source of drinking water for the Florida Keys, which is pumped from wells in South Dade County. Drinking water for Palm Beach County north of Boca Raton, except West Palm Beach, is supplied by another component of the surficial aquifer that is not as productive as the Biscayne Aquifer. West Palm Beach is the only major municipality supplied by surface water; the source is Clear Lake just inland from the coast (C&SF FCD 1973; Haire and Shaw 1989; Klein et al. 1975; SFWMD 1992, 1993, 1994a; Yoder et al. undated). Some local governments in Broward County have investigated use of the Upper Floridan Aquifer as a water supply (Teets et al. 1991).

The LEC's natural drainage pattern of streams and transverse glades has been almost totally altered and replaced by a man-made system of canals. Roughly 3.2 million acre-ft per year (more than 1000 billion gallons per year) of freshwater empty to coastal estuaries through 28 main canals of the C&SF Project. Half of these are in Dade County and discharge into Biscayne Bay (Cooper and Lane 1987a,b, 1988; SFWMD 1993). Discharges include stormwater, drainage water from agricultural and urban land, excess water from the WCAs, and water released to the LEC to recharge groundwater and prevent saltwater intrusion. Volume, timing, and distribution of present discharges are thought to differ substantially from discharges received by estuaries prior to development of the C&SF Project and precursor drainage works. Another system of canals, the South Dade Conveyance System, delivers a mandated supply of water to ENP and also supplies water to other South Dade canals to prevent saltwater intrusion (Cooper and Lane 1987b; Wedderburn et al. 1981). Drainage of interior wetlands has lowered the water table, altered natural groundwater flow, eliminated coastal springs and artesian wells, and increased amplitude of seasonal hydrologic fluctuations along the LEC (Buchanan and Klein 1976; Fish and Stewart 1991; Parker 1984; Parker et al. 1955; Teets et al. 1991). In the early 1960s, small springs were still discharging through the bay bottom along shore south of Miami; discharges were great enough to cause salinity-based biological zonation (Kohout and Kolipinski 1967).

Saltwater intrusion has been a concern for most of this century and the object of detailed study since 1939, when saltwater appeared in the Miami wellfield more than 10 km (6 mi) inland from Biscayne Bay. In 1941 saltwater forced abandonment of the coastal groundwater supply in Coconut Grove (Brown and Parker 1945). The greatest encroachment occurred between 1943 and 1946 during an extended drought (Schroeder et al. 1958). Lowering of water levels was reported in 1952 to have already caused abandonment of tomato farms in South Dade County because of saltwater encroachment and increased subsoil salinity (Egler 1952). The canals induced intrusion by draining away fresh water stored in the aquifer and serving as a route for seawater to extend inland during droughts (Brown and Parker 1945; Parker 1951, as cited in Schroeder et al. 1958). The costly solution was installation of salinity gates in most canals and abandonment of other coastal wellfields. Because of the threat of saltwater intrusion, levels of fresh water near the saltwater interface must be maintained higher than sea level (Klein et al. 1975; SFWMD 1992; Schroeder et al. 1958; Trimble 1986; Walters 1987). Saltwater intrusion because of high aquifer pumping rates is a primary threat to drinking water supplies in coastal Broward and Palm Beach counties; Broward has been forced to shut down many wells because of saltwater intrusion (Joint Center 1988a; Rodis and Land 1976; Teets et al. 1991).

Desalination is a process used to produce fresh water in Florida since 1967, especially on the Southwest Coast and in the Keys (SFWMD undated(c)), but it has not been used extensively in Subregion 9. In 1987, one Palm Beach County utility was using reverse osmosis technology to supply some potable water, and a few other communities were investigating the technology (Khanal 1987). Source water for desalination can be seawater or brackish aquifer water, such as from the Floridan aquifer (Morin 1987).

Agriculture

Agriculture is an important land use throughout Subregion 9 and provides large areas for aquifer recharge (SFRPC 1991). It comprises the major land use west and south of the Coastal Ridge (Parker et al. 1955). Prior to arrival of the railroad, only subsistence farming was practiced. The few attempts at farming on a commercial scale, principally pineapples, quickly failed because of lack of cheap labor to harvest crops. Also, the only means to transport freight was by ship. The first reported shipment of vegetables (tomatoes and eggplant) left Dade County in 1882. After completion of the railroad in the 1890s, the companies sold much of their land to farmers and encouraged agriculture as an alternate revenue source to balance seasonal tourism. By 1930 agriculture was

established as a major industry (Nicholas 1974; Winsberg 1991). Vegetable production gained national importance after World War II when family disposable income increased and consumption of fresh vegetables, instead of canned or stored, was no longer a luxury (Winsberg 1991).

Agricultural lands in Subregion 9 are concentrated in the 388-km^2 (150-mi^2) South Dade Agricultural Area near Homestead. More than 90,000 acres were mapped as agricultural land in 1985 (SFWMD 1992, 1993), and over 80,000 acres were harvested in 1986-87 (Dade DERM 1990a). Vegetables account for 56% of total sales value. These include 18 kinds of traditional vegetables and 6 tropical vegetables, such as malanga and boniato. Winter tomatoes are the largest cash crop, followed by bush and pole beans, new potatoes, and yellow squash. Sweet corn and seed corn are also grown. Nurseries, including field, container, and greenhouse operations, account for 30% of agricultural value. Fruit crops contribute the remaining 14%. Many area crops are not grown commercially anywhere else in the U.S. Dade County is one of the few places in the U.S. where tropical fruits (10 varieties including carambola, passion fruit, and lychee) are grown, and it produces almost all the U.S. supply of Persian limes, mangoes, and Key limes (PBSJ 1992; SFWMD 1992, 1993; Winsberg 1991).

Farming in South Dade requires extensive site preparation. After the vegetation is bulldozed, surface rock is scarified, or rockplowed, with heavy equipment to form a uniform planting medium of rock fragments and pulverized limestone with a little soil (Anderson 1986; DOI 1973; Mierau 1975; Snyder 1986; Waller 1982, 1983). Besides site preparation efforts, other stages of crop production are extremely energy intensive. Heavy applications of fertilizers, most trucked in, are needed for maximum yields. An estimated 80% of truck crops and fruit trees require irrigation. Heavy use of oil-based pesticides is also required, and it is now common to use thousands of acres of petroleum-based plastic sheeting as mulch (Anderson 1986; Dade DERM undated(e), 1990a, 1991; Mierau 1975; Scheidt 1989; Snyder 1986; Winsberg 1991). The drainage basin of Biscayne Bay is 24% agricultural land. In this basin, an estimated 445,000 lbs of the 35 most common pesticides are used per year (246,000 lbs of herbicides; 125,000 lbs of insecticides; and 74,000 lbs of fungicides) (Pait et al. 1992). A calculation based on harvested acreage and recommended application rate per acre for each product gives an estimated total annual use in Dade County of 8 million lbs of active ingredient represented by 74 different pesticides (Scheidt 1989).

Prior to the C&SF Project, farming practices in South Dade had been adapted to the natural variability of Everglades flooding and drying. Land preparation and planting would not begin until wet-season water levels naturally receded, normally in December. This changed in the 1980s, partly because of a lower than normal decade of rainfall, which allowed grove crops requiring year-round low groundwater levels to expand westward. Economic pressures also forced row crop farmers to plant as early as October. Both factors led to additional demands to lower canal operational stages. These lowered water levels were a primary factor in increased agricultural and residential development in low-lying areas of western Dade County, even west of the eastern protective levee, and also in other western portions of Subregion 9 (COE 1994; Anderson 1986; Leach et al. 1972; C&SF FCD 1974; McPherson et al. 1976).

Agricultural lands in eastern Palm Beach County include 14,000 acres of citrus and 15,000 of vegetables. Commercial horticulture is also important, and acreage of nurseries is predicted to double by 2010 (SFWMD 1993). In 1980 Palm Beach County designated a 26,000-acre tract between the Florida Turnpike and Loxahatchee NWR as an Agricultural Reserve Area. In addition to preserving agriculture, the designation limits development density and attempts to discourage county expenditures for urban services in the area (Joint Center 1988a).

Broward County's land use plan also calls for preservation of agricultural and rural lands (Broward Bd. Commiss. 1989a), but urbanization is expected to continue to reduce agricultural acreage. The Broward agricultural area covered 6000 acres in 1989; down from 13,000 acres in 1950 and a reported 34,000 acres in 1935 (Broward Bd. Commiss. 1989b; Winsberg 1991). Although land devoted to ornamental nurseries is expected to increase, acreage in vegetables and citrus may decrease to only double digits by 2010 (SFWMD 1993).

Invasive Nonindigenous Species

The LEC is the center of distribution of non-native plant and animal species introduced into the South Florida environment, primarily because of the importance of Miami and Fort Lauderdale as ports of entry for shipments from foreign countries. Miami International Airport receives 85% of all shipments of plants to the U.S.

(Frank 1994a; OTA 1993). Historically, Dade County near Coral Gables was a location where melaleuca (*Melaleuca quinquenervia*) was originally planted in the early 1900s, and melaleuca seeds were released by airplane over western Broward County in the 1930s (LaRoche and Ferriter 1992). In some cases, exotic plants have totally replaced native habitats; e.g., wet prairies have been replaced by melaleuca stands (Austin 1976; Richardson 1977). Over 300 species of exotic plants are known to be naturalized in natural community fragments in Dade County south of the Miami River (Gann-Matzen 1994). The Dade County Park and Recreation Department is involved in intensive exotic removal and maintenance of natural areas to prevent permanent damage to these areas from invasive non-native plants, especially exotic vines, following Hurricane Andrew in 1992 (Flynn 1994; Gann-Matzen 1994; Horvitz 1994; Klein undated; McHargue and Hammer 1994; Thayer and Ferriter 1994). Rockplowed farm areas in South Dade County that are abandoned or left fallow are prime sites for colonization by invasive non-native species that threaten nearby natural areas (Alexander and Crook 1973; Dalrymple et al. 1993; Doren et al. 1990; Egler 1952). Native vegetation does not easily reestablish once the substrate has been altered as drastically as it is in rockplowing (Snyder 1986). The non-native submersed aquatic plant hydrilla (*Hydrilla verticillata*) is a continuing problem for the SFWMD, especially in canals of Dade and Broward counties. As hydrilla is removed, *Hygrophila*, another submersed aquatic tolerant to most herbicides, has expanded (Thayer and Ferriter 1994).

The FWS identifies 82 nonindigenous fish species in Florida, many of which occur in South Florida (McCann et al. 1995). Cichlids, such as the oscar and spotted tilapia, have been extremely successful in establishing populations throughout Subregion 9. Dade County is probably most affected; nearly all of its fresh and brackish waters, especially the canals, were infested by the early 1970s (Courtenay and Hensley 1979; Hogg 1976; Kushlan and Lodge 1974). In the 1950s, canals in southern Dade County were inhabited by native killifishes and livebearers, sunfishes, and largemouth bass; now they are dominated by South American, Central American, and African fishes. Palm Beach County canals are being invaded by species expanding their ranges northward (Courtenay 1994a). Peacock bass, introduced into LEC canals to control other nonindigenous fish and as a game fish, is slowly outcompeting native bass and bream (OTA 1993). Non-native marine fishes, many from the Bahamas and Indo-Pacific, occur in coastal waters. With few exceptions, escape from aquarium culture is the source of nonindigenous fishes in open water (Courtenay 1994a,b).

Many other fauna have also invaded the LEC. South Florida has more introduced and established reptiles and amphibians than any other area in the U.S. These now include the South American caiman in Dade County (Ellis 1980; McCann et al. 1995; Wilson and Porras 1983), large constricting snakes, and large predaceous monitor lizards. The boa constrictor is reported to be breeding in Dade County. All of the almost 30 nonindigenous reptiles and amphibians known in Florida are found in South Florida, with the greatest concentration in the Miami area. Because Miami is a major center for international pet trade, many of these species were introduced as accidental or purposeful releases and first observed in urban areas of Dade County (Dalrymple 1994; King and Krakauer 1966; Wilson and Porras 1983). This also applies to avifauna, for which there is a large cottage culture industry in South Florida. Many pet birds simply escape and survive. Species with self-sustaining populations include monk parakeet, canary-winged parakeet, red-whiskered bulbul, and spot-breasted oriole. Several others, including common myna, may be establishing wild populations (James 1994). Non-native mammals also occur in the LEC; several are established, including coyote, red fox, three species of monkey, and possibly white-nosed coati (Layne 1994).

Insects, snails, and other invertebrates arrive as stowaways on shipments through ports of entry (Daigle 1984; McCann et al. 1995; OTA 1993; Roessler et al. 1977; Russo 1973). Two exotic insects that recently invaded the LEC are threatening native plants. A weevil that feeds on native bromeliads was discovered on introduced bromeliads in a Broward County nursery and subsequently found on public lands in all three counties. Wild pine and giant wild pine are favorite bromeliad targets and have been reclassified from threatened to endangered status by the Endangered Plant Advisory Council because of the weevil's impact (Duquesnel 1994b; Frank 1994b). A neotropical tortoise beetle from South America and the Antilles, which feeds on native morning-glory and also sweetpotato, was discovered in Broward County in 1993 and has since been found in other locations, including parks in Dade County. Hurricane Andrew is suspected as the mode of its introduction, possibly on plants imported to replace those destroyed by the storm (Duquesnel 1994a; Thomas 1994). Other nonindigenous insects discovered since the hurricane include a citrus leafminer, two species of avocado leafminers, a cricket that oviposits on lychee trees, a lychee mite, two types of scale insects, and three species of thrips (Thomas 1994).

Protected Species

In Subregion 9, 23 animal species and 8 plant species might be found that are Federally listed as threatened or endangered (J. Carroll, FWS, pers. comm.; Coile 1993; FWS 1980a, 1980b, 1990, 1993, 1994; Kale 1978; Layne 1978; McDiarmid 1978; R. Pace, FWS, pers. comm.; Wood 1994).

County lists prepared by FWS indicate six Federally listed endangered plants occur in Palm Beach, Broward, and Dade counties (FWS 1994): crenulate lead-plant (*Amorpha crenulata*), deltoid (wedge) spurge (*Chamaesyce deltoidea* ssp. *deltoidea*), Small's milkpea (*Galactia smallii*), tiny milkwort (polygala) (*Polygala smallii*), four-petal pawpaw (*Asimina tetramera*), and beach clustervine (*Jacquemontia reclinata*). A seventh plant, Garber's spurge (*Chamaesyce garberi*), is Federally threatened. Carter's mustard (*Warea carteri*) is a Federally endangered species that, although not on the FWS county list, is reported by the State to occur in Broward County; it has been extirpated from Dade County (Coile 1993; Wood 1994). The State plant list maintained by the FDACS Division of Plant Industry shows at least 65 endangered species occur in one or more of the three counties (Coile 1993; Wood 1994).

The crenulate lead-plant, deltoid spurge, Small's milkpea, and tiny polygala are now found only in Dade County pine rocklands (Dade DERM 1993a); the tiny polygala, extant in Dade County, was extirpated from Broward County (Coile 1993). Garber's spurge, also a rockland species, occurs in the Florida Keys in addition to Dade County. These five species are endemic only to South Florida pine rocklands (Dade DERM 1993a). Pine rockland plants are rare because of habitat loss, and the State lists 32 such plants as endangered or threatened (Dade DERM 1994b).

The four-petal pawpaw occurs in scrub and scrubby flatwoods in Palm Beach and Martin counties. The beach clustervine, a perennial vine of dunes and strand openings, occurs in Palm Beach, Broward, and Dade counties.

Federally listed endangered or threatened animals that reside in or move through Subregion 9 are:

Reptiles:	Atlantic loggerhead turtle, Atlantic green turtle, Atlantic hawksbill turtle, leatherback turtle, Atlantic ridley turtle, American alligator, American crocodile, Eastern indigo snake, Atlantic salt marsh snake.
Birds:	Florida scrub jay, bald eagle, wood stork, snail kite, piping plover, roseate tern, red-cockaded woodpecker, Cape Sable seaside sparrow, Audubon's crested caracara, Kirtland's warbler, Bachman's warbler.
Mammals:	West Indian manatee, Florida panther.
Invertebrates:	Stock Island tree snail.

Sea turtles (primarily loggerheads, greens, and leatherbacks) nest along the entire LEC, especially in Broward and Palm Beach counties. The southeast coast of Florida supports more than 97% of the State's nesting and is one of the four major loggerhead rookeries in the world. Juvenile green turtles are frequently observed by divers along nearshore hardbottom areas of Palm Beach County. Many human conflicts occur as a result of beach development, including night beach lighting and pedestrian traffic (Broadwell 1992; Burney 1994; Burney and Mattison undated; Burney et al. 1990, 1994; Burney and Margolis 1993; Conley and Hoffman 1987; Fletemeyer undated, 1977, 1983, 1984, 1990, 1991; Harris et al. 1984; Leone-Kabler et al. 1994; Mann 1977; Margolis 1993; Mattison et al. 1990; Milton et al. 1994; NMFS/FWS 1991a, 1991b, 1992, 1994; Reiners et al. 1994; Salmon et al. 1994; Teas, W., pers. comm.; Town of Palm Beach 1993; Wershoven, J.L., and R.W. Wershoven 1992; Wershoven, R.W., and J.L. Wershoven 1989, 1992; Witherington 1990; Witzell, W., pers. comm.; Wolf 1989). In addition to beach development, threats to turtles include recreational reef diving, boating activities, and frequent freshwater discharges from canals during heavy rainfall. These discharges may be linked to algae blooms that outcompete preferred algal forage (Wershoven, R.W., and J.L. Wershoven 1992). Hurricanes can also cause significant nest mortality (Leone-Kabler et al. 1994; Milton et al. 1994).

The alligator is a common resident of LEC wetlands, even in urban areas. This often results in conflicts in residential subdivisions built along lakes or canals and on golf courses with lakes. The alligator is now listed as

threatened because of similarity of appearance to the crocodile. Crocodiles apparently inhabited most creeks and swamps north to Hallandale, including tributaries to Biscayne Bay, and also Virginia Key; historical reports indicate occurrence as far north as Lake Worth. They nested along Biscayne Bay as far north as Miami Beach. As late as 1967, a 6-foot crocodile was shot on Miami Beach. The crocodile's favored natural habitat -- saltwater marshes with sandy, undisturbed high spots -- has been almost completely destroyed. During 1977-80 surveys, crocodiles were found residing in power plant canals in Fort Lauderdale; in 1978 one was shot in Fort Lauderdale. The crocodile's territory in Subregion 9 is now virtually restricted to extreme southeast Dade County at Turkey Point Nuclear Power Plant, where nesting has been documented since 1978. This site is one of three major crocodile nesting areas in South Florida; the other two are ENP and Crocodile Lake National Wildlife Refuge on north Key Largo. The power plant site is ideal habitat with 270 km (168 mi) of cooling canals, abundant food, and secure nesting sites on spoil berms along the canals. It contributes about 10% of the hatchlings to the South Florida population. Crocodiles have also nested along Highway 1 between the mainland and Key Largo (Gaby et al. 1985; Garlock 1994; Kushlan 1988; Kushlan and Mazzotti 1989; Ogden 1978). Hatchlings tagged on Key Largo during 1978-91 were recovered on the mainland as far as 113 km (70 mi) away in Fort Lauderdale. Juveniles from all three major nesting areas have been found along the mainland shoreline between U.S. 1 and Card Sound Road. Highway mortality along U.S. 1 south of Florida City is the greatest identifiable cause of crocodile deaths (Moler et al. 1992). Their range was bisected by U.S. 1, forcing them to cross the highway in order to move through the range. Several upgrades planned for U.S. 1, such as fencing and special underpasses, may reduce this mortality (FHWA/FDOT 1992).

Although it is protected, collection of the indigo snake constitutes the most profitable illegal trade in Florida (Enge 1991). This snake adapts moderately well to disturbed areas, and southeast Dade County supported the largest population of this species in South Florida (Wilson and Porras 1983). The Atlantic salt marsh snake occurs only in Palm Beach County (FWS 1994).

Decline of the scrub jay throughout its range is attributed almost entirely to loss of scrub vegetation habitat to agriculture, silviculture, and commercial and residential development. It is listed only from Palm Beach County and might be found in scattered patches of scrub along coastal sand ridges, such as the Yamato Scrub (Fernald 1989; Fernald and Toland 1991; Fitzpatrick et al. 1991). The wood stork, bald eagle, and snail kite would most likely be seen in remote western portions of Subregion 9, adjoining the WCAs and ENP. Wood storks and snail kites are found in the extreme southern and southeast wetlands of Dade County (Alleman et al. 1995a; FHWA/FDOT 1992). A pair of bald eagles unsuccessfully tried to nest in the early 1980s on Virginia Key in urban Dade County (Evoy and Schechtman 1986); this is the only eagle nest site indicated for Subregion 9 by FGFWFC (Cox et al. 1994). The caracara and red-cockaded woodpecker are listed only for Palm Beach County. The Cape Sable seaside sparrow might be found in prairies bordering the southern Everglades and in the Model Lands area of extreme southeastern Dade County. The two listed warblers are extremely rare and might only be encountered during migration.

The manatee, a coastal resident throughout the LEC, is seriously endangered by interactions with man, especially collisions with boat propellers and drowning in flood gates and drainage culverts. During severe cold weather, manatees regularly seek refuge in warmwater outfalls at the Port Everglades Power Plant and Dania cutoff canal in Broward County. Dade County presently has no artificial warmwater refuges that operate regularly and are used by manatees (Dade DERM 1994a; FWS 1980b). A draft plan was recently issued by the COE to reduce manatee mortality at water control structures by using pressure sensors to reverse direction of the gates when resistance is encountered (COE 1995).

Florida panthers have been tracked along the fringes of agricultural and suburban developments in South Dade County; two were found dead in South Dade in August 1991. One panther tracked by radiotelemetry frequently crossed U.S. 1 just south of Florida City, and another is known to occasionally range in the area west of U.S. 1 and south of the C-111 (FHWA/FDOT 1992). Panther territory has also been documented between Card Sound Road and Turkey Point Power Plant (Cotleur Hearing 1995). The southeastern beach mouse, a Federally threatened species, historically occurred in Subregion 9 south to Hollywood Beach in Broward County. Intense development eliminated all suitable habitat (relatively undisturbed beach dunes with extensive sea oat zones seaward of intact secondary dunes) in Broward, and the beach mouse has most likely not survived in either Broward or Palm Beach counties. According to the FGFWFC, appropriate habitat does not now extend as far south as the LEC. One

or two sites in Palm Beach County might be able to support populations if beach dune habitat is restored and maintained (Cox et al. 1994; Humphrey et al. 1987; Robson 1989a).

Populations of the Stock Island tree snail (Federally threatened) and Florida tree snail (State species of special concern, see below) were present at Monkey Jungle south of Miami, where they had been transplanted. These included many varieties and forms now extinct in the Keys. Only a few days after Hurricane Andrew devastated hammock habitat at Monkey Jungle in 1992, an effort was initiated by FWS and the University of Florida to rescue the snails, which were exposed to direct sunlight because of canopy loss, and house them until the hammock could recover (Emmel 1992).

In addition to the Federally listed animals, several others in Subregion 9 are listed as endangered or threatened by the State of Florida (Wood 1994). The Florida mastiff bat is listed as endangered because of habitat loss and human persecution. It has been recorded from Broward County but primarily occurs in urbanized Dade County; most recent records are from Miami and Coral Gables (Robson 1989b; Robson et al. 1989). The Arctic peregrine falcon, also listed as endangered, is a migrant through the area and also a winter resident (Kale 1978). Peregrines often follow barrier beaches, and Bill Baggs Cape Florida SRA on Key Biscayne is a significant migration point for the species (Evoy and Schechtman 1986). The white-crowned pigeon, reported to nest along lower Biscayne Bay (Alleman et al. 1995a), is considered threatened by the State. The FGFWFC indicates occurrence along the Dade County shoreline in the Coral Gables area (Cox et al. 1994). The least tern, impacted by human interference in its beach nesting areas, is also classed as threatened. These terns formerly nested intensively along causeways and dredge fills in Biscayne Bay (Evoy and Schechtman 1986; Owre 1976). A 1974 survey documented least tern nesting on rooftops of shopping malls, supermarkets, and office buildings in several LEC locations (Fisk 1975). The Miami blackheaded (rimrock crowned) snake is another State-threatened species.

The State of Florida also classifies certain animal species as "species of special concern." Those occurring in Subregion 9 include Florida tree snail, gopher tortoise, burrowing owl, brown pelican, black skimmer, Sherman's fox squirrel, Florida mouse, Florida gopher frog, several wading birds (e.g., roseate spoonbill, little blue and tricolored herons, snowy and reddish egrets), and two fish species (common snook and mangrove rivulus) (Wood 1994).

The Florida tree snail is found only in the southern part of the LEC. It was historically widely distributed in tropical hardwood hammocks that lined the Coastal Ridge as far north as Boynton Beach in Palm Beach County, with snails in each hammock exhibiting a different color form. As intense development began leveling most of the hammocks even before 1900 (including those in Boca Raton and Fort Lauderdale, Yamato Hammock in Boynton Beach, and the vast Brickell Hammock in Dade County), tree snails were greatly reduced. Now populations survive primarily in remnants of hammocks preserved as parks (Bayer 1948; Clench 1946; Craig 1973; Montgomery 1975; Simpson 1929; Voss 1976).

The gopher tortoise occurs in isolated populations south to north Dade County. It is an important ecosystem component because of the ecological value of its burrows; 360 species of animals, including other protected species (e.g., indigo snake), use these burrows and some cannot exist without them (Cox et al. 1987; Puckett and Franz 1991). A 14-acre tract of scrub at Fort Lauderdale Executive Airport is managed as a gopher tortoise preserve (Broward Bd. Commiss. 1993b). The Coastal Ridge is an area of concentration for the burrowing owl, but it exists only in scattered populations. Areas of sandy scrub, such as in southwest Broward County, were ideal habitat prior to development (Cox et al. 1994; Millsap undated). The owl has tried to adapt to habitat alteration by nesting in locations such as airport runways, golf course sand traps, and children's sandboxes (Consiglio and Reynolds 1987). Fort Lauderdale Executive Airport is also working to protect more than 100 burrowing owls nesting on its property (Blom 1994).

Rookeries important to many protected wading birds are among the most conspicuous natural features of the coastal area. Large Dade County rookeries exist at Greynolds Park in North Miami; Bird Key and other spoil islands in North Biscayne Bay; and Virginia Key, Key Biscayne, and Chicken Key in Central Biscayne Bay. In Palm Beach County, a rookery exists on Fisherman's Island in Lake Worth. In Broward County, rookeries occur on islands in lakes at Fort Lauderdale Executive airport and a power plant (Alleman et al. 1995a; Kushlan and White 1977; Metro-Dade Plan. Dept. 1988a; Nesbitt et al. 1982; Osborn and Custer 1978).

MAJOR ISSUES

The major ecosystem issues that confront Subregion 9 are:

- Human population growth.
- Land development.
- Water conservation for wildlife and human populations.
- Quantity and quality of freshwater flow to estuaries.
- Quality of groundwater and inland surface water.
- Preservation and restoration of natural areas.
- Loss of habitat for protected and other native species.
- Invasive nonindigenous species.
- Limited Federal responsibility.
- Lack of common understanding and perspective about the environment.

Human Population Growth

In 1890, the population of the area encompassing the current Dade, Broward, and Palm Beach counties was 861 people, with Palm Beach County almost uninhabited. By 1900, just after arrival of the railroad, the population had grown almost six-fold to 4,955 (Nicholas 1974). Between 1900 and 1990, the population increased more than 800-fold to 4,056,228 (Bur. Econ. Bus. Res. 1994). The highest rate of growth in Subregion 9 occurred between 1910 and 1930, during the land boom that peaked in 1925. The population almost quadrupled during the decade 1910-20 and more than tripled during 1920-30. It almost doubled during each of the following decades 1930-40 and 1940-50 and more than doubled again between 1950 and 1960. In the next 30 years to 1990, although the rate of growth slowed, population of Subregion 9 still almost tripled (Bur. Econ. Bus. Res. 1994; Shultz 1991).

Although Dade County has the largest population, which surpassed 2,000,000 in 1995 (Hancock and Keating 1995), the other two counties have exhibited the highest growth rates. Over the past two decades, Dade County population increased by 53%, while Broward County grew by 102% and Palm Beach County by 147% (Bur. Econ. Bus. Res. 1994; SFWMD 1993). Broward County was the most rapidly growing county in the U.S. between 1950 and 1970; the population increased by 298% (quadrupling) during 1950-60 and 86% during 1960-70 (Nicholas 1974; Shultz 1991). Since 1990 Broward has added more new residents than any other Florida county (Hancock and Keating 1995). The population of one Broward community, Pompano Beach, increased almost 700% between 1950 and 1970 and changed from an agricultural community to a residential city with a shoreline dominated by highrise condominiums (Moran 1979). During 1950-60, the population of Palm Beach County also exploded and almost exactly doubled. More recent growth rates have been lower but still high; 64% in Broward and 65% in Palm Beach during the 1970s, 23% in Broward and 50% in Palm Beach during the 1980s (Bur. Econ. Bus. Res. 1994; SFWMD 1993; Shultz 1991).

The populations of Dade and Broward counties are projected to grow 30-40% between 1990 and 2010. For the same period, the Palm Beach County population is projected to increase by 85% to 1.6 million (Bur. Econ. Bus. Res. 1994; SFWMD 1993). Noncoastal Palm Beach County, west of Interstate 95, is predicted to show the highest growth in the subregion during the 1990s (Shultz 1991). The sheer size of the LEC population and its continuing expansion, with its attendant demands and needs for land and services, has changed the entire natural South Florida ecosystem and contributes to most of the problems addressed in this chapter (DOI 1973; Joint Center 1985a, 1988a; McCluney and McCluney 1969; SFWMD 1994a; Rich 1969; SFRPC undated; Tarnow 1969).

Land Development

Intense development has occurred along the LEC for most of this century. In 1927, naturalist R.M. Harper reported "developers" in South Florida were "trying to destroy the vegetation as fast as possible, to make room for cities and farms," and areas of vegetation he had studied in prior years were gone forever. He was concerned developers were working faster than botanists and destroying plants before they could be studied. Harper specifically mentioned that much of Brickell Hammock near Miami was being turned into valuable building sites (Harper 1927). The World War II military buildup of South Florida provided a basis for rapid development. Between 1940 and

1970, the area of urbanized land in Broward County alone increased 14-fold. Development first followed the coastline and transportation routes from south to north, turning the Atlantic Coastal Ridge into a strip megalopolis; it then turned west (Nicholas 1974). Expansion of urban development to interior areas, many of which were previously uninhabitable due to frequent flooding, has been possible only because of flood control provided by the WCAs and C&SF Project canals (C&SF FCD/Dade Co. 1959; Kohout and Hartwell 1967; Leach et al. 1972). Westward expansion of development in Subregion 9 continues to convert wetlands and agricultural fields to housing subdivisions, roads, shopping centers, commercial strip complexes, and office buildings. Both urban and agricultural developments are still expanding westward into wetlands just east of the WCAs and ENP and continuing to erode water storage capacity. Most new residents of each of the three counties settle in noncoastal inland areas (Shultz 1991; Teets et al. 1991).

Some of the most rapid development and extensive proposed development is occurring in the C-9 basin of southwest Broward County (SFRPC 1989, 1990), much of which is flood-prone wetlands with poor drainage (Broward Bd. Commiss. 1989b; BCPC 1989b, 1991; C&SF FCD 1976; Teets et al. 1991). Recent construction has included major expressways, office and industrial parks, and an outlet mall claimed as the world's largest (Muller 1991). An area here (identified as "flood prone" and "wetland" in the Broward County Master Plan), and including part of northwest Dade County, was the site of the proposed 2,500-acre Blockbuster Park sports and entertainment complex. Before being withdrawn in late 1994, this project was rapidly moving through the approval process at both local and State levels, which included the State relinquishing a wetland area to Dade County to facilitate the development. The Superintendent of ENP stated it was short-sighted to make such land use commitments while Everglades restoration studies were underway and proposed these changes "might make restoration strategies problematic - and maybe impossible." (Zaneski 1994a). It has been emphasized that great caution must be exercised in development of this area because of low topography, lack of slope, poorly drained soils, and potential for long periods of standing water (Broward Bd. Commiss. 1989b; Burns et al. 1982). The sensitivity of this area was realized many years ago. In 1976 voters supported a moratorium on growth in the area, and in 1981 the Broward planning agency determined it should be declared an area of local critical concern and development should be discouraged. Still, however, 45% of Broward's new-home demand is for houses in southwest Broward (Sheridan 1994). In February 1994, a Miramar developer's proposal to build almost 4,000 homes near U.S. 27 in this area was just narrowly defeated by the Broward County Commission (Tanfani 1994). In comments on this proposal to the Board of Commissioners, the Superintendent of ENP requested it be deferred, if not denied, until completion of South Florida restoration and water supply planning efforts. He stated that further development in remaining wetlands would make it difficult for Broward County to assure long-term water supplies and flood control and would severely constrain options for Everglades restoration (Ring 1994).

Several conferences have addressed environmental issues in Broward County. In 1988, the SFRPC assembled a group to compile and analyze information available on the western C-9 basin in order to aid permitting and land use decisions (SFRPC 1989, 1990). In 1992 a conference sponsored by the Broward Department of Natural Resources Protection addressed the county's environmental future (Joint Center 1993). The 1995 C-9 Basin Design Workshop and Roundtable addressed suburban sprawl in this same area and its effects on water and other resources. More than 100 citizens, environmentalists, developers, planners, and representatives from local and regional governments discussed competing interests and if development can be designed to respect limits and resources (FOF 1995b,c). The result was a concept plan presented to the Governor's Commission for a Sustainable South Florida. The major feature of the plan is a system of canals and rivers that would form a regional stormwater system designed and built by the SFWMD. In 1996 the SFWMD is scheduled to complete an assessment of flood problems in the C-9 basin (SFWMD 1994a).

Land development impacts water supply because it reduces areas of standing water and often leads to a lowering of the water table. Because the surficial aquifer is so permeable, lowering the water table in one area affects the water table for miles around. Stormwater discharge increases after land is developed, not only because of additional drainage works to provide flood control, but also due to creation of impervious surfaces such as parking lots, roads, foundations, and patios. This loss of permeable open space reduces infiltration into soils and groundwater and reduces aquifer recharge potential (Browder 1991; Browder et al. undated; C&SF FCD 1973; Joint Center 1988a; Moran 1979). A recent Miami Herald article publicized these problems and emphasized water management experts have difficulty predicting results of disaster-level flooding from heavy rainfall because so much of Dade and Broward counties has been paved in the last 20 years (Russell 1994). It is not known what would

happen during situations such as August-September 1981, when Homestead recorded 49 inches of rain from Tropical Storm Dennis and other subsequent storms and a large portion of South Dade was flooded for more than 2 months (SFWMD 1982b); or January 21, 1957, when the area west of West Palm Beach received 21.5 inches of rain (COE 1992).

Increased density of development and urbanization in western portions of Subregion 9 and its effect on flooding risk have been major concerns for regulatory agencies for many years, especially how to continue providing drainage improvement without encouraging intensified development (Burns et al. 1982; C&SF FCD 1973, 74, 1976; Joint Center 1985a; Khanal 1975, 1982; Kohout and Hartwell 1967; Leach et al. 1972; McCoy and Hardee 1970; SFWMD 1984b, 1987; Whalen and Cullum 1988). The SFWMD District Water Management Plan states "urbanization of the western subbasins is not consistent with the original design level of flood protection for the area" (SFWMD 1994a). A major canal system redesign effort is underway in Palm Beach County, necessitated by flooding in the now urbanized western portions of the C-51 basin. Development in this area has already surpassed the land use projection for the year 2025 as estimated in 1972 (COE 1992). Between 1971 and 1976, a development company observed a 1.8-2.4 km (6-8 ft) drop in the water table in one area of Palm Beach County being urbanized (Richardson 1977). The area around Cypress Creek Canal in Pompano Beach, historically a cypress slough, became a flood hazard after urbanization (Moran 1979). Even where only minimal encroachment into wetlands occurs, impacts are widespread. In far west Dade County, canal stages have been regulated to benefit isolated agricultural and residential communities established in unprotected wetlands. This has further lowered the water table, which has decreased the hydroperiod in wetlands of ENP and reduced freshwater flow to Florida Bay (COE 1993; Van Lent et al. 1993).

Land development affects water quality through chemical contamination, principally by stormwater runoff, and through saltwater intrusion caused by excessive withdrawals from the aquifer. Contributing to contaminant loads are lawn fertilizers, pesticides, and pet wastes from residential areas; metals and solvents from industry; fuel, grease, and oils from highways, parking lots, and airports; and leachates from landfills (Alleman et al. 1995a,b; Area Plan. Bd. Palm Beach Co. 1974; Broward Bd. Commiss. 1993b; Hardee et al. 1979; Holler 1989; Howie and Waller 1986; Klein et al. 1975; Klein and Hull 1978; Mattraw and Miller 1981; Mattraw and Sherwood 1977; Mattraw et al: 1978a,b; Miller and Mattraw 1982; Moran 1979; Waite and Greenfield 1977; Waller 1982, 1983; Waller et al. 1984; Weinberg et al. 1980; Whalen and Cullum 1988).

Even obtaining building material has impacted wetland habitat. Considerable mining for limestone rock occurs in Dade and Broward counties, mainly in a strip of 41,000 acres of degraded wetlands between the urban area and the WCAs. More than half the construction-grade rock used in the entire State of Florida is supplied by Dade County. Products include cement and asphalt, limerock road base, riprap for shoreline erosion control, and materials for septic tank drainfields, stormwater seepage trenches, and treatment plant filters. Each year, mining directly transforms 300-400 acres of land into deep lakes (Larsen Assoc. 1992; NW Dade Freshw. Lake Plan Implem. Comm. 1995), which often become centerpieces of real estate developments. Besides destroying wetlands outright, this process drains the surrounding area by concentrating water in the pits. Also, these pits are direct connections to the aquifer, with potential for excessive evaporation and groundwater contamination (DOI 1993, 1994; Teets et al. 1991).

Recent GIS analyses illustrated the pronounced urban encroachment on the western edge of the LEC urban area; in many locations encroachment on natural areas is more intense than would be expected from population growth and housing construction data (Walker and Solecki 1994). As westward development proceeds, the SFRPC has emphasized the necessity of balance between development, available infrastructure and water supply, natural resources, and quality of life (C&SF FCD 1974; SFRPC 1989). Palm Beach County attempted to limit westward growth in 1980 when it designated its Agricultural Reserve Area. One objective was to discourage county expenditures for extension of services such as water and sewer lines, schools, and fire protection beyond the designated Urban Service Area (Joint Center 1988a). The Broward County comprehensive plan provides exceptions from level of service standards to encourage building in urban areas already developed and to discourage urban sprawl and reduce development pressures on rural and agricultural areas. (Broward Bd. Commiss. 1993a).

Planners involved in post-hurricane reconstruction of South Dade County are attempting to address cumulative impacts of development and integrate land use with natural resource and water quality values during

redevelopment. Ideas have emphasized reclamation and protection of wetlands and other natural areas, protection of water quality and quantity, and rebuilding in existing urban areas instead of in peripheral undeveloped areas (Alleman 1995; Alleman et al. undated; Joint Center 1993; SFWMD undated(a); UM/FIU 1992). It is interesting to note that in 1970 a 24-km (15-mi^2) shoreline area of South Dade was proposed for development, with a South Bay Parkway (first proposed in 1962) and high-density housing clustered around a series of marinas and a major inland waterway. As many as 350,000 to 480,000 people were envisioned living there (Metro-Dade Plan. Dept. 1970).

One large infrastructure project planned for Dade and Monroe counties is the widening to four lanes of the 32-km (20-mi) section of U.S. 1 from Florida City to Key Largo. Key Largo is a favorite weekend destination for LEC residents and tourists because of its recreational opportunities and proximity to Miami (FHWA/FDOT 1992). Recent objections to the project have centered on secondary and cumulative impacts of improved travel to and from the Keys, not just on Key Largo but the entire length of the Keys (Ferrell 1994; Hall 1995).

County planning documents emphasize that land development and population growth must be managed in an ecologically compatible manner consistent with environmental protection (Broward Bd. Commiss. 1989a,b, 1993a,b; Metro-Dade Plan. Dept. 1988a,b, 1989, 1993). However, it often appears most land development occurs without adequate consideration of ecosystem impacts, including water use, hydrologic changes, and elimination of wildlife habitat. It is usually not recognized that controlling development is necessary to preserve the economic base as well as the natural environment. Upland and wetland areas are important as wellfield sites, and uplands serve as recharge areas. Wetlands provide storm protection and floodwater retention and function as water purifiers. Beaches provide recreational opportunities and support tourism, while the dunes provide storm protection. Coastal mangroves contribute directly to sustainability of fisheries (Gleason 1984; SFRPC 1991). In many cases, development costs are increased by destroying the self-managing capabilities of natural communities (Browder et al. undated; McCluney and McCluney 1969).

Water Conservation for Wildlife and Human Populations

Demand for water by the LEC is out of phase with the distinct seasons of the natural hydrologic cycle; it is highest during the dry season (November through May) when only 35% of the rainfall occurs (Browder et al. undated; Leach et al. 1972; Lin et al. 1984; SFWMD 1992, 1993; Storch 1975). Demand on the public water supply is expected to increase enormously. Demand for the year 2010 is projected to increase over 1990 demand by 43% in Dade County, 68% in Broward County, and 115% in Palm Beach County (SFWMD 1993). Excessive withdrawals from the surficial aquifer can cause problems such as shortening of the hydroperiod in nearby wetlands and saltwater intrusion into drinking water supplies (Leach et al. 1972).

A major issue in Subregion 9 is the waste of great quantities of stormwater and treated effluent released to the ocean. Discharges from coastal water control structures for drainage and flood control in the LEC developed area have been estimated at about 9082 acre-ft per day or 2960 million gallons per day (MGD) [1080 billion gallons per year (BGY)]. This is equivalent to about 43% of the total outflow of 6850 MGD (2500 BGY), which includes other outflows such as wellfield pumpage, groundwater and overland flows, and evapotranspiration (SFWMD 1993). In addition, roughly 588 MGD (214 BGY) are lost to the system as treated wastewater effluent; 60% is discharged to the ocean, 40% is injected into deep wells (1991 data, SFWMD). At least 400 MGD of this treated effluent, or 68% of the total, are suitable for recovery for irrigation. Florida statutes require water reuse feasibility studies. The Administrative Code requires water management districts to designate critical water supply problem areas and make reuse mandatory within those areas, unless reuse is not economically, environmentally, or technically feasible. It also requires reuse feasibility studies for new or expanding wastewater facilities discharging to surface waters (Adams et al. 1984; PBSJ 1992). Reuse is the application of reclaimed water for beneficial purposes, such as landscape or agricultural irrigation, groundwater recharge, industrial use, or environmental enhancement such as wetlands restoration (DOI 1973; SFWMD 1992). Wastewater reuse could help mitigate present or future inadequacies in the regional water supply during a drought. Reuse could substitute for other changes to the system as a method to improve water supply. This approach is most applicable when reuse involves water that would have been disposed of by deep-well injection or ocean outfall. If it substitutes for percolation, benefits to the regional supply would be greatly reduced (Adams et al. 1984).

In a regional evaluation by the SFWMD, the three LEC counties represented 73% of the potential capacity for wastewater reuse in South Florida; Palm Beach County alone represented 34% (Adams et al. 1984). Some reuse systems have been implemented in municipalities and developments in Subregion 9. In 1991, Pompano Beach was reusing up to 2.5 MGD of effluent from one ocean outfall. South Broward Utilities was reusing wastewater through a multicell percolation pond system for groundwater recharge. One Broward County regional plant and the City of Hollywood were developing reuse projects. Hollywood was also investigating feasibility of using treated wastewater as a hydrodynamic salinity control barrier (Teets et al. 1991). In 1992, the City of Boca Raton was initiating an extensive dual reclaimed water system to reduce potable water consumption and saltwater intrusion (SFWMD 1992). The majority of reuse systems use treated effluent to irrigate golf courses or other landscapes. Use of wastewater was primarily an economic decision because it was a low-cost disposal method. Some systems were discontinued in the 1980s in favor of deep-well injection disposal when surface water discharge regulations became more stringent. For example, requirements for backup systems increased costs of water reuse, and treating wastewater for reuse often became more costly than procuring water from alternative supplies (Joint Center 1985b,c,d). A feasibility study done in Palm Beach County by the SFWMD found few existing treatment plants or irrigation users would voluntarily participate in a wastewater reuse system because it would not be economically advantageous (Adams et al. 1984).

Backpumping represents a structural approach to water conservation in which excess stormwater runoff is pumped westward back into storage areas; i.e., WCAs (SFWMD 1992; SFWMD 1982a). Primary problems associated with backpumping are the expense of building and operating large-capacity pumping facilities and potential adverse environmental impacts of periodically storing large volumes of runoff of unacceptable quality that might cause nutrient loading or pesticide contamination (FWQA 1970; Waller 1978). Backpumping into the WCAs from urban areas for flood protection and water supply has resulted in some water quality and biological impacts, including increased nutrient concentrations at perimeter sites (SFWMD 1994a; Teets et al. 1991). Backpumping has been evaluated in most SFWMD basins (COE 1992; C&SF FCD 1973, 1976; DOI 1973; Kohout and Hartwell 1967; SFWMD 1992; SFWMD 1984b). Presently the only backpumping operation in Subregion 9 diverts about 6% of total structure outflow from the LEC developed area into WCA 3A from the western C-11/South New River basin in Broward County (CH2M Hill 1994; Pfeuffer 1985; SFWMD 1984a; Teets et al. 1991; Waller 1978). Construction of STAs under the Everglades Forever Act will include redirection of discharges from the planned C-51 West End Flood Protection Project in Palm Beach County to STA 1E, a constructed wetland of 5350 acres, and then to WCA 1, instead of to the Lake Worth estuary (Burns & McDonnell 1994).

Davis (1943), in discussing the need for water reservoir areas five decades ago, emphasized water conditions in the Everglades must be considered in maintaining water supplies for coastal cities. Recently, several proposals have been presented for water preserves and buffer areas along the western edge of the LEC, adjacent to the WCAs and ENP. These include water reuse impoundments (Orians et al. 1992), stair-stepped marshes (NAS 1994), a belt of lake preserves in the rock-mining area (Larsen Assoc. 1992), and the conceptual plan for a stormwater system in the western C-9 basin (FOF 1995c,d). Another proposal is to strengthen the eastern boundary levees to allow greater seasonal storage and reduce discharge to tide, while still controlling urban flood risk (Orians et al. 1992). In 1992, State legislation created the Northwest Dade County Freshwater Lake Plan Implementation Committee. This is a public and private partnership charged with planning a freshwater lake system to replace the mosaic of quarried lakes created by rockmining (NW Dade Freshw. Lake Plan Implem. Comm. 1995). Also, as part of the C&SF Project Comprehensive Review Study and Lower East Coast Water Supply Plan and in cooperation with NAS, the East Coast Buffer Project was formulated by the COE and SFWMD. The Buffer concept has wide support and would include undeveloped parcels totaling over 63,000 acres of wetland marshes and deepwater reservoirs that will separate many areas of the Everglades from urban and agricultural areas. The objective of the project would be to improve hydroperiods of wetlands east of the East Coast Protective Levee; reduce seepage losses from the WCAs; increase groundwater recharge and surface and subsurface water storage for urban, agricultural, and environmental systems; improve quality of water delivered to the Everglades from the C&SF Project; provide protection for urban drinking water wellfields; provide habitat for plants and animals in and adjacent to wetlands; eliminate exotic plants in historically wet areas; and provide recreational opportunities for LEC residents (COE/SFWMD 1995; CH2M Hill 1994; Jackson and Stroud 1995; Hoffman 1994; Neuharth 1995). Data collection is in progress for a COE Environmental Impact Statement on the Lake Belt preserves, with Dade County leading studies on habitat and ecology evaluation, EPA leading water quality evaluation, and several other

cooperators involved (G. Miller, EPA, pers. comm.; NW Dade Freshw. Lake Plan Implem. Comm. 1995; Nova Univ. 1995; Yoder 1993).

A major use of water in Subregion 9 is for landscape irrigation, especially during the dry season. Average annual irrigation demand by golf courses in the three counties is expected to be more than 37 BGY by 2010, with 23 BGY in Palm Beach County alone (SFWMD 1993). Xeriscaping is intensively promoted as a water conservation technique in urban areas, especially by the SFWMD (SFWMD 1992; SFWMD undated(b),(d),(e)). The FDOT plans to initiate a policy that all wildflowers used in State highway landscaping must be native species (L. Burnett, FDOT, pers. comm.) and is experimenting with plantings of saw palmetto, which does not need irrigation or pesticides (C. Higgins, FDOT, pers. comm.; Kollin 1994). The Dade County master plan calls for xeriscapes and native landscapes wherever feasible, especially in salt-intruded areas where public water is used to water lawns, golf courses, and other landscaped areas (Metro-Dade Plan. Dept. 1993).

A policy statement on growth management in Palm Beach County listed water needs of native ecosystems as an issue needing consideration (Joint Center 1988b). A major project related to water conservation for wildlife is investigating effects of increased water deliveries to Taylor Slough in ENP (COE 1993). A negative human impact of these deliveries may be increased flooding potential in agricultural and residential areas just east of the Park, due to higher canal stages and groundwater levels. The SFWMD considers increased water demands and associated drawdowns of groundwater a threat to short-hydroperiod wetlands in the western portions of Subregion 9 (SFWMD 1992, 1993). Development of methods to increase the urban area's self-sufficiency for water needs is a major step in expanding water storage capacity of the Everglades system (Orians et al. 1992).

Quantity and Quality of Freshwater Flow to Estuaries

Estuaries, as receiving areas for canal releases, are being detrimentally affected by sporadic, short-term, extraordinarily high-volume canal discharges that occur repeatedly each year. Biscayne Bay is especially impacted, and the primary goals of the SFWMD Biscayne Bay SWIM Plan are to improve water quality and restore more natural freshwater flow to the bay (Alleman et al. 1995a,b; SFWMD 1995). Releases from the C-111 canal into Manatee Bay, which opens into Barnes Sound at the south end of the Biscayne Bay system, are an extreme example of sporadic discharge (Browder 1991). Lake Worth is also subject to extremes of freshwater discharge (COE 1992; C&SF FCD 1973). Stormwater discharges to Lake Worth will be reduced when releases from the C-51 west basin are redirected to STA 1E as discussed above (Burns & McDonnell 1994). Estuaries are also stressed during the dry season by long periods with little or no surface freshwater inflow. This is exacerbated by elimination of the natural slow seepage of groundwater from the Coastal Ridge caused by lowering of the water table.

Most surface runoff of nutrients and contaminants from agriculture and urban land uses is discharged to estuaries. These contaminant loads are not being adequately regulated to prevent damage to coastal ecosystems. Existing laws, standards, regulations, and enforcement may all be insufficient. Poor water quality in canals discharging to LEC estuaries was a concern two decades ago (Birnhak 1974). The SFWMD considers stormwater runoff the source of most water quality problems, especially in Biscayne Bay (Alleman et al. 1995a,b; SFWMD 1994a).

A system that rates intensity of "hazard normalized application" of agricultural pesticides by calculating pounds applied per acre of drainage area per year ranked Biscayne Bay the second worst estuary in the U.S. for per-unit-area application of the more hazardous pesticides. Applications of the insecticides endosulfan (37,000 lbs in the Biscayne Bay watershed) and chlorpyrifos (6,000 lbs) were most responsible for the rating. Endosulfan is commonly applied to tomatoes and is the most hazardous pesticide in the marine environment because of its acute toxicity, ability to concentrate in fish tissue, and long time needed to break down (Humphreys 1993; Pait et al. 1992). Much of the agricultural watershed of South Dade County drains into Florida Bay and south Biscayne Bay. A decade ago, endosulfan was among several contaminants found in sediment porewater collected from 11 of 17 stations in BNP near the discharge of Black Creek, which carries much agricultural drainage (Corcoran et al. 1987). A recent preliminary pesticide survey found quantifiable levels of endosulfan at most stations sampled in the C-111 canal system and at one station in Florida Bay. Highest levels were found in C-111 near the entrance to ENP. Contaminant concentration of agricultural nonpoint source runoff must be considered in management plans to increase freshwater flow to the Everglades (Scott et al. 1994b, 1995b).

Quality of Groundwater and Inland Surface Water

Because of the Biscayne Aquifer's shallow depth and permeability, groundwater contamination is a constant threat in Subregion 9 (SFWMD 1994a). Numerous contamination sites have been identified in the three counties; some of these are close to active public water supply wellfields. Cleanup of these sites or other protective measures may be necessary before additional wellfields can be developed. Dade County alone has over 4700 hazardous materials sites, 175 industrial waste sites, and 140 agricultural waste disposal sites (SFWMD 1993). In 1993, more than 5600 hazardous waste generators were identified in the three counties; more than 2400 were in Dade County. The LEC has 20 waste sites on, or proposed for, the Superfund National Priorities List for remediation. Dade County has 12 of these, including Homestead Air Force Base where soil and groundwater have been contaminated by fuels, solvents, pesticides, and metals. Other Superfund sites in the subregion include landfills, a municipal incinerator, alloy and plating facilities, and chemical and petroleum product industries that release a wide range of contaminants (EPA 1982, 1985a,b,c, 1986, 1987a,b, 1990c,d, 1993, 1994d).

Since an EPA survey in the 1970s revealed synthetic organic chemicals in both raw and treated water of Dade County's North District water supply, many groundwater quality studies have been conducted by EPA and Dade County DERM. A close relationship was shown between presence of industrial development above the cones of influence of public wells and presence of volatile organic chemicals in the water supply, which led to development of wellfield protection ordinances (Walters 1987; Yoder et al. undated).

A problem in some LEC water treatment plants is the high organic content of groundwater. Dissolved organic carbons in raw water supplies interact with chlorine in water treatment to form trihalomethanes (Klein and Hull 1978; Symons et al. 1975; Teets et al. 1991; Walters 1987). Animal studies indicate THMs represent a cancer risk. In 1975, EPA reported over 300 ppb chloroform and almost 6 ppb vinyl chloride in Dade County drinking water. This prompted EPA-funded research by Florida International University and Dade County on methods to remove THM precursors (Wood et al. 1980, 1984). Since 1981, the regional water utility in Dade County has controlled THM formation by modifying the chlorination process, and all Dade water utilities meet the current drinking water limit for THMs (H. Kottke, pers. comm.). In 1992, installation of air strippers was completed at treatment facilities serving northern Dade County. Most of the $40 million construction cost was provided by EPA with the purpose of removing certain industrial groundwater contaminants. This process is also very effective in further reducing THM levels. Emissions from the air stripping process meet current air pollution criteria, but air pollution control equipment (scrubbers) may be needed if more stringent regulations are enacted in the future (J. Baker, pers. comm.; H. Kottke, pers. comm.). Officials of Sunrise in Broward County have also had to reduce THM levels in water supplied to several municipalities (Miami Herald 1994). The waters from Lake Okeechobee and the WCAs, which help to recharge the Biscayne Aquifer by canal flow, are naturally clear if not disturbed (Gleason and Spackman 1974). The main source of the THM problem may be drainage of organic Everglades soils, which is causing subsidence and release of dissolved organic carbons (Reddy 1982).

Groundwater contamination is possible in agricultural areas because of extensive use of chemicals (pesticides, herbicides, fertilizers) if BMPs are not used, especially in those areas near wellfields (Anderson 1986; Baker 1988; Dade DERM undated(e), 1990a, 1990b, 1991, 1992a; SFRPC 1991; Yoder et al. undated). Several studies concluded agriculture is a major contributor to elevated levels of fertilizer components in groundwater, public drinking water supplies, and private wells (Baker 1988; Dade DERM 1991; Yoder et al. undated). Septic tank effluent (Pitt 1974; Pitt et al. 1975; Waller et al. 1987), lawn chemicals, dump leachate (Schneider 1973), and stormwater runoff from urban areas (e.g., from highways, Howie and Waller 1986), can also pollute groundwater. In 1976 Dade County declared a temporary moratorium on extensive agricultural and residential development in the East Everglades because of concern about water quality (of both groundwater and surface water) and other environmental changes. In 1978, the Dade Planning Department was given responsibility to determine how the area functions and to develop BMPs (Waller 1983). Evaluation of risks to groundwater from agrichemical use is difficult because of inadequate data on local usage and lack of a central repository of such data. Several regulations require recordkeeping but either do not require consistent reporting to regulatory agencies or require reporting only when threshold amounts are exceeded (Dade DERM 1991; Scheidt 1989).

A major factor in LEC water management is the high degree of hydraulic connectivity between the Biscayne Aquifer and the canal system; contaminants found in the inland canals can directly impact the quality of groundwater

(Allman et al. 1979; FWQA 1970; Klein and Hull 1978; Yan et al. 1995). Use of pesticides in or near wetlands or adjacent to water bodies or wellfields is a particular concern. To reduce potential herbicide runoff to surface waters, the FDOT discontinued broadcast spraying of herbicides statewide in July 1994 (L. Burnett, FDOT, pers. comm.). Nemacur, whose active ingredient is fenamiphos, is often used on golf courses to control nematodes in turf and is highly toxic to wildlife. Half of all wildlife kills investigated by the FDACS in the State since 1991 involved Nemacur. The media have reported recent kills of fish and ducks following applications of Nemacur to area golf courses and subsequent runoff into surface waters after heavy rains. Leaching of Nemacur into groundwater is a serious concern. The U.S. Golf Association found fenamiphos contaminated 9 of 24 monitoring wells tested in Florida, and the EPA has expressed concern about contamination of drinking water by fenamiphos since 1990. A geologist for the FDEP recommended a ban on use of Nemacur in sandy ridge soils until methods to establish setbacks from wellfields are determined (Zaneski 1994b). The manufacturer of Nemacur recently agreed to restrict its use in order to reduce the chance it will wash into waterways (Zaneski 1995). The threat of Nemacur is amplified in Subregion 9 because of the vast number of golf courses and the area's heavy summer rainfall, combined with the pesticide's high solubility. Some studies have been done on the use of biocontrol agents to control turf pests and reduce application of chemical pesticides. This work includes control of mole crickets on LEC golf courses (Frank 1994c).

The supertoxic organochlorine insecticide endosulfan is not a restricted-use pesticide, and there is no current documentation of its use in Dade County or elsewhere in South Florida. An estimated 28,500 lbs of endosulfan active ingredient were applied just to Dade County tomatoes in 1988; it is also used on several other vegetables and nursery plants. Measurements by Scott et al. (1994b, 1995b) of pesticides in surface waters of Florida Bay and adjacent agricultural canals of South Dade County indicated 14% of stations sampled had detectable levels of pesticides, including endosulfan at levels exceeding the Florida regulatory limit and chronic water quality criterion. Field monitoring and laboratory toxicity testing will continue during 1995-97 to further assess impacts on Florida Bay of contaminants in surface runoff from the agricultural watershed (Scott et al. 1995a,b). In the early 1980s, sediment contaminants were present in most canals emptying into Biscayne Bay, and endosulfan was among the compounds detected in sediment porewater in South Biscayne Bay near canal discharges (Corcoran et al. 1987). Dade County DERM found endosulfan in 5 of 139 samples from private wells in South Dade in the late 1980s. Since 1991, pesticide monitoring by the SFWMD has detected endosulfan or a degradation product in surface water and sediments in several South Dade canals (Scheidt 1995). Enforcement of water quality standards for pumped effluents on the agriculture industry has not been effective (DOI 1994).

Preservation and Restoration of Natural Areas

Natural habitats of the LEC, now scattered in fragments within the urban/agricultural landscape, are so reduced in extent that any example of a natural community in good condition is considered an environmentally sensitive area. Destruction of the hammocks by development was reported decades ago (Alexander 1958; Phillips 1940). Large-scale clearing of pinelands for row crops followed development of rockplowing machinery in the 1950s (Snyder et al. 1990). By 1984, Dade County had lost 98% of its pineland and tropical hammock habitat to logging, urban development, or agriculture, most rapidly between 1940 and 1970 (Loope et al. 1979; Snyder 1986). This loss is continuing (Cox et al. 1994; FDEP 1995). Only about 4000 acres of pinelands remain outside ENP (FDEP 1995; Klein undated).

Urban development has also eliminated most scrub and coastal upland habitat. Palm Beach County has lost 98% of its Atlantic coastal scrub; what remains is fragmented and surrounded by developed or disturbed land. The largest and most diverse tract remaining is the 249-acre Yamato Scrub along I-95. In 1989 this tract, then proposed for development, was recommended as a scrub preserve (Fernald 1989), and it is on the CARL Program list for acquisition (FDEP 1995; Palm Beach DERM undated, 1991). The FNAI found only 650 acres of coastal upland natural communities remaining in all of Subregion 9, comprised of 136 acres of beach dune vegetation, 165 acres of coastal strand, and 349 acres of coastal hammock, scattered over 16 sites (Johnson et al. 1993). The FNAI found development in Dade and Broward counties has been so complete it is difficult to reconstruct the composition and structure of natural coastal uplands in sufficient detail for community restoration (Johnson and Muller 1993).

Nonindigenous invasive plants are a major threat to preservation and restoration of natural areas. In a 1994 statewide survey, Dade County was one of six counties reporting these species on 100% of its natural lands; almost

half of the areas are moderately to severely infested. Broward County reported occurrence of greater than 97%, with severe or moderate infestation on 95% of its natural areas. Palm Beach County reported occurrence of 56%, with 31% moderately to severely infested (Gregg 1994). In Hillsboro Beach Estates in Broward County, designated a coastal upland natural area by the FNAI, an invasive philodendron has so thickly blanketed the ground that establishment of native tree seedlings might be prevented (Johnson et al. 1993).

Hurricane Andrew devastated areas of native plant communities in southern Dade County, reversing restoration progress and creating severe threats especially to upland hammocks and pinelands. Hardwood hammocks are being invaded by non-native species and some native vines at an unprecedented rate. If left unchecked, these plants would drastically alter hammock composition and structure (Flynn 1994; Gann-Matzen 1994; Klein undated; McHargue and Hammer 1994). Most native pines that survived the storm have been infested by pine bark beetles and killed by an associated fungus (Dade DERM 1993a, 1994b; Dade PRD 1994a). The hurricane demonstrated that effective management is critical to long-term maintenance of natural areas in the urban environment. Natural areas are not as resilient to storm disturbance as they once were because urban development has reduced the amount of native seed and, through landscape plantings and formation of new habitat (cleared land, canal banks, drained wetlands, etc.), has created an enormous seed bank of invasive species. Some foresters speculate that the lowered water table in southern Dade County had stressed the pines before the storm and made them more susceptible to disease following the storm. Fire exclusion also has worked against long-term survival of pineland, which is a fire subclimax community. Along with reforestation, appropriate fire regimes must be restored (Dade PRD 1994b,c; Snyder et al. 1990).

Several county, State, and cooperative efforts have been initiated in hurricane-damaged areas of Dade County and also in areas that serve as mitigation banks. State and county governments have undertaken a number of natural community restoration projects, many of which were drastically altered or accelerated in Dade County by Hurricane Andrew. The restoration project at storm-ravaged Cape Florida SRA on Key Biscayne may be the largest ever undertaken in the U.S. (FDEP 1993). The Dade County program to restore hurricane-damaged hammocks is the largest local natural areas restoration project in the country (M. Gregg, Dade PRD, pers. comm.). All these efforts include intensive removal of invasive non-native species; fostering remnant mangrove, coastal strand, wetland, and hammock communities; and extensive planting of native vegetation. Florida also has an ongoing program of restoring natural native vegetation in State parks. However, well documented restoration methodologies are lacking for South Florida vegetation communities. Planting experiments and adequate monitoring and documentation from which to develop better methodologies for future projects may not be conducted for lack of funds and in some cases lack of understanding of the need by decision makers.

Despite dramatic reduction in natural lands, active land management has contributed much towards preservation in recent years. A policy statement on growth management in Palm Beach County recommended permanent protection for native ecosystems, restoration of those already damaged, and protection and acquisition of land for conservation and recreation (Joint Center 1988b). All three counties have recognized loss of natural areas as a critical issue and instituted programs to purchase sensitive lands for preservation. More than 16,000 acres of natural areas are managed by Palm Beach (6,424 acres), Dade (6,398), and Broward (3,283) counties (Gregg 1994). Almost all coastal uplands identified by the FNAI are in public ownership as State, county, or city parks (Johnson et al. 1993). Much habitat, however, is still unprotected. About 2200 acres of Dade County pinelands outside ENP and 350 acres of hammock are still privately owned. Of endangered plant species in Dade County, 70% are located on private lands (Klein undated). Many preserved lands protect populations of endangered plants; other lands, such as those in mitigation banks, are restored to native vegetation. Some of these purchases are arranged through the CARL or SOR programs. Many parcels of pine rocklands and hammocks in Dade County are on the CARL list for acquisition (several are already purchased) as the Dade County Archipelago (FDEP 1995).

Dade County's covenant program for protecting privately owned natural areas, renewable at the end of 10 years, has not been entirely successful (DERM undated(c)). Although landowners receive a tax exemption, only 177 acres of land, including some pineland, are under the program. Existing penalties do not adequately prevent land from being removed from covenants before the end of the 10 years and sold for development. Loss of standing pines from Hurricane Andrew caused some privately owned pineland under the program to be removed prematurely. Pines might have regenerated on some of this land had it not been cleared by landowners giving up their covenant agreements.

Remnants of natural communities, even though preserved or restored, are subject to continued stress because of fire suppression, alteration of natural hydrology, exotics invasion, and other factors. For instance, eradication of exotics will be a constant task because of persistent invasion from surrounding areas. Because of these stresses in combination with severe fragmentation, most small natural areas, particularly upland forests, are not ecologically sustainable and will require active management in perpetuity (Drum 1993; Gann-Matzen 1994). Local governments, however, are acquiring natural areas to save them from development without having dedicated funding for the ongoing management that will be needed (Gregg 1994).

Loss of Habitat for Protected and Other Native Species

The great loss of habitat resulting from extensive land development in Subregion 9 has almost eliminated some types of vegetative communities from the landscape. In 1970, almost all of the coastal forests had been destroyed (100% of those in Broward County, 96% in Palm Beach County, and 92% in Dade County), along with most of the scrub in Palm Beach County, pinelands and mangroves in Broward County, and wet prairies in Broward and Palm Beach counties (Birnhak and Crowder 1974). Many natural area land purchases in the subregion are made to preserve habitat for remnant populations of endangered plants. The amount of protected habitat remaining is so small, however, it does not guarantee the future of threatened and endangered species or other native species. Also, conflicts between development and protected species habitat are almost a daily occurrence in the urbanized area.

Large areas of coastal Palm Beach County that historically supported scrub communities are no longer recognizable as scrub soils and are now designated as urban lands or other unnatural substrates in soil surveys (Fernald 1989). Scrub habitat contains a high proportion of endemic plants; in Atlantic coastal scrub, 37% of the species are endemic (Lovestrand 1990). Remaining pineland habitat is so fragmented it soon may not adequately support pineland fauna. Pinelands remaining in the urban area are threatened by habitat conversion, invasion of nonindigenous plants, and fire exclusion; without fire pine rocklands succeed to hardwood hammocks (Bentzien 1987; Doren et al. 1993; Loope et al. 1979). Pineland habitat is designated by the FNAI as imperiled in the State and also globally (Cox et al. 1994; Dade PRD 1994b; Gann-Matzen 1994). It is very vulnerable to development; several sites proposed for the CARL Miami Rockridge Pineland acquisition in 1986 have been destroyed and Hurricane Andrew impacted others (Cox et al. 1994). It is possible many endemic plant taxa of the pinelands will be lost because only about half of the species are protected in ENP (Snyder 1986). A study of pineland species richness showed substantial variation among study sites, indicating remnant fragments of pineland are extremely important in preserving biological diversity.

Destruction of natural cover is a major factor in reduction of native amphibian and reptile populations (Wilson and Porras 1983). The greatest threat to gopher tortoise conservation is extensive land alteration that accompanies urbanization (Cox et al. 1987). The Florida mastiff bat is considered endangered by the State partly because of loss of native forested habitat. To prevent further bat population decrease, it was recommended in 1989 that steps be taken to preserve remaining pine, live oak, and tropical hardwood hammock habitat in Dade and Broward counties (Robson 1989). The FGFWFC developed a system that ranked the 668 regularly occurring vertebrate taxa in Florida according to biological vulnerability and status of knowledge of distribution, population trends, limiting factors, and conservation efforts. These rankings demonstrated the high relative importance of coastal regions, especially for reptiles, birds, and mammals. Coastal uplands (beach strands and maritime hammocks), habitats now almost totally lost in the LEC, stood out as important habitat for large numbers of vulnerable taxa (Millsap et al. 1990). Only three natural coastal upland areas (> 10 acres) remain in Dade County. One of these, a hammock on Virginia Key, is on City of Miami land recently proposed for development as a commercial campground; this project was rejected by voters in November 1995. Although it was to include exotic removal and restoration of native vegetation, the development was planned to accommodate 500 campsites (Biolog. Environ. Consult. 1995; Johnson et al. 1993; Paddon and Suman 1995). The FNAI found only three remaining natural coastal upland sites entirely or partly in private ownership and thus potentially available for public acquisition (one in Palm Beach, two in Broward, and none in Dade); these total only 58 acres. Opportunities for preserving additional natural coastline in Subregion 9 are therefore few (Johnson et al. 1993).

Invasive Nonindigenous Species

In the early 1970s, Alexander and Crook (1973) warned aggressive non-native plants were "at the threshold of an overpowering population explosion" in South Florida. Vast numbers of centers of distribution (foci) of exotic plants make their total eradication almost impossible (LaRoche and Ferriter 1992). The most effective means of controlling the spread of melaleuca is eradication of the most isolated seed trees, or outliers (Browder and Schroeder 1980; Woodall 1980), which are foci of distribution. This may also result in successful control of other invasive exotics in urban areas of Subregion 9.

Anthropogenic habitats abundant in the LEC, such as abandoned farmland, levees, berms, canals, and roadfill sites, are prime colonizing sites for exotic plants (Alexander and Crook 1973, 1984; Egler 1952). Loxahatchee NWR has one of the most severe infestations of melaleuca because of its proximity to numerous urban plantings made in the Palm Beaches (OTA 1993). Additional species continue to be introduced into the environment by the nursery, pet, and aquarium trades. The magnitude of its international trade makes Miami the port of entry for many introductions. Vast numbers of plants (330 million in 1990) and animals pass through Miami International Airport each year, most from Latin America (OTA 1993). Ecological impacts of the many species of exotic animals present in, or passing through, Subregion 9 are largely unknown. Present regulatory mechanisms cannot keep pace with the increase in commercialization and quantities of imports. Thousands of boxes of tropical fish alone arrive each week; it is impossible for each shipment to be inspected for prohibited or restricted species (Quinn 1994).

Importation and sale of non-native plant species is largely uncontrolled. There is no mechanism in place for screening and restricting importation of new invaders. The focus of the Animal and Plant Health Inspection Service is on importation of species that are risks to agricultural activities, not those that are risks to natural communities. The FWS, through the Lacey Act, prevents entry of a short list of "injurious" taxa: 2 families, 13 genera, and 6 species. Efforts by FWS to add species to the Lacey Act have met successful opposition from the hobby trade. The Florida Division of Plant Industry, which sets standards for the nursery trade, makes no attempt to judge ornamental plants for "weediness" or invasive tendencies. Many plants, in addition to the few that are well known, pose threats to natural areas. Many of these have been identified by the FLEPPC (1995). There is little, if any, government oversight on sale and distribution of species identified as invasive problem species in Florida by the FLEPPC.

Scientifically based criteria have not been developed for screening nonindigenous species to support possible future controls. A protocol is needed to help set priorities for management measures at all possible stages -- from restrictions on importation, propagation, and sale to removal or biological control. Except for melaleuca and a few other species, the spread of invasive species is not being monitored. Despite several successful cooperative activities concerning high-profile species, there is no coordinated approach to the generic problem of invasive non-native species. Needed is the appointment of lead agencies and personnel at all governmental levels (Federal, State, and local) to develop an approach that includes management initiatives and supportive science.

Limited Federal Responsibility

The Federal government has limited jurisdiction over factors relevant to South Florida Ecosystem Restoration in the urban and agricultural areas of the LEC. The EPA, FWS, USDA, COE, and NOAA, through Sea Grant and the National Marine Fisheries Service, have various levels of science, land stewardship, or regulatory responsibilities in this area. Some of these activities are handled through grants to State and local agencies. The State also has some oversight or regulatory responsibility (e.g., FDEP, FGFWFC, FDACS, FDCA), but primary responsibilities reside with a multitude of municipal, county, and regional governmental and quasi-governmental agencies, in addition to many special taxing districts. The number of municipalities that control land use just in the Biscayne Bay planning area totals 32 (Alleman et al. 1995a).

A serious obstacle to solving growth problems is the absence of formal political institutions or a coordinated approach to address the entire range of issues and their cumulative impacts. This was reported specifically for Palm Beach County (Joint Center 1988a,b) but applies to all of Subregion 9. The Federal government does not always know what State and local governments are planning that could affect the restoration effort. Impacts of Federal

programs on the urban/agricultural environment are great. A recent report summarized these impacts on Everglades wetlands (DOI 1994). A similar effort should address all habitats in South Florida.

Lack of Common Environmental Understanding and Perspective

During the 1980s, more than 85% of the population increase in Subregion 9 was due to immigration of residents from other places. Dade County is the only one of the three counties where natural births contributed a significant proportion (37%) of the increase. People from the Northeast U.S. dominate migrants to both Broward and Palm Beach counties, with more than 40% of the total. The Northeast is also the major source of U.S. migrants to Dade County, with one-third of the total, but this is equaled by international immigration. The LEC is the only area of South Florida where migration from other countries is significant; the destination of these immigrants is usually Dade County (Kerr 1991; Shultz 1991).

The great diversity of the LEC population makes it difficult for scientists or managers to use only one message to promote environmental protection, wildlife preservation, or water conservation. The population includes many different races and income levels; large numbers of non-native residents, including immigrants and retirees; and several transient groups, including tourists and seasonal residents. Each group looks at its impact on the environment with a different perspective and responds differently (Duda 1987). Societal preferences for environmental preservation also differ among groups (Drum 1993). The Hispanic population of Dade County grew by 64% during 1980-90; that of Broward grew by 169% (SFRPC undated). Recognizing this, SFWMD has initiated an outreach program directed at the Hispanic community of Dade County to inform it about South Florida's water resources and how it can help protect these resources (SFWMD 1994b).

It is often difficult for residents to understand environmental changes in the coastal area because the direct cause may be many miles away (Browder et al. undated). The many residents who have improved their economic status by immigrating to South Florida do not see the threats to their standard of living caused by a shrinking resource base (Craig 1991). Also, many residents have lived in the area for such a short time they do not understand its environment or its problems (Gleason 1984). Much of the Southeast Florida economy is based on providing services for retirees and tourists, and both groups are in the area only temporarily. Tourists make little commitment to their destination. Retirees, whose numbers may significantly increase in the area as the baby boom generation ages, are often still loyal to their former homes and not to the local area. They also are usually reluctant to pay for projects with large upfront expenditures and delayed benefits (Kerr 1991; Stronge 1991); ecosystem restoration projects take years if not decades. Surveys, however, indicate most homeowners consider wildlife and natural habitats in urban areas very important (Duda 1987). As related to gopher tortoise conservation, the FGFWFC considers preserves in urban areas a very valuable method of education. Establishing effective education programs as part of long-term goals for tortoise protection areas is an important consideration (Cox et al. 1987). This applies to other species as well.

The LEC megalopolis has developed into one of the nation's most attenuated linear cities, 160 km (100 mi) long and an average 16 km (10 mi) wide. In such a sharply elongated form, the urban area becomes a checkerboard of independent segments, which leads to a problem of unity (Muller 1991). Development of a unified public vision of environmental quality may be the greatest challenge for Everglades restoration.

INFORMATION NEEDS

The goal, objectives (based on SSG 1993), and information needs for Subregion 9 are summarized in Figure 18. Most major issues presented in this chapter are addressed by the three counties in their comprehensive master plans and other planning documents (Broward Bd. Commiss. 1989a,b, 1993a,b; Metro-Dade Plan. Dept. 1988a,b, 1989, 1993). The appendix to this chapter summarizes many of the science projects already conducted or initiated in the LEC to address the issues identified for the subregion. Generally, the projects listed in the appendix are limited to those conducted over the past 20 years; earlier work was cited in the text above.

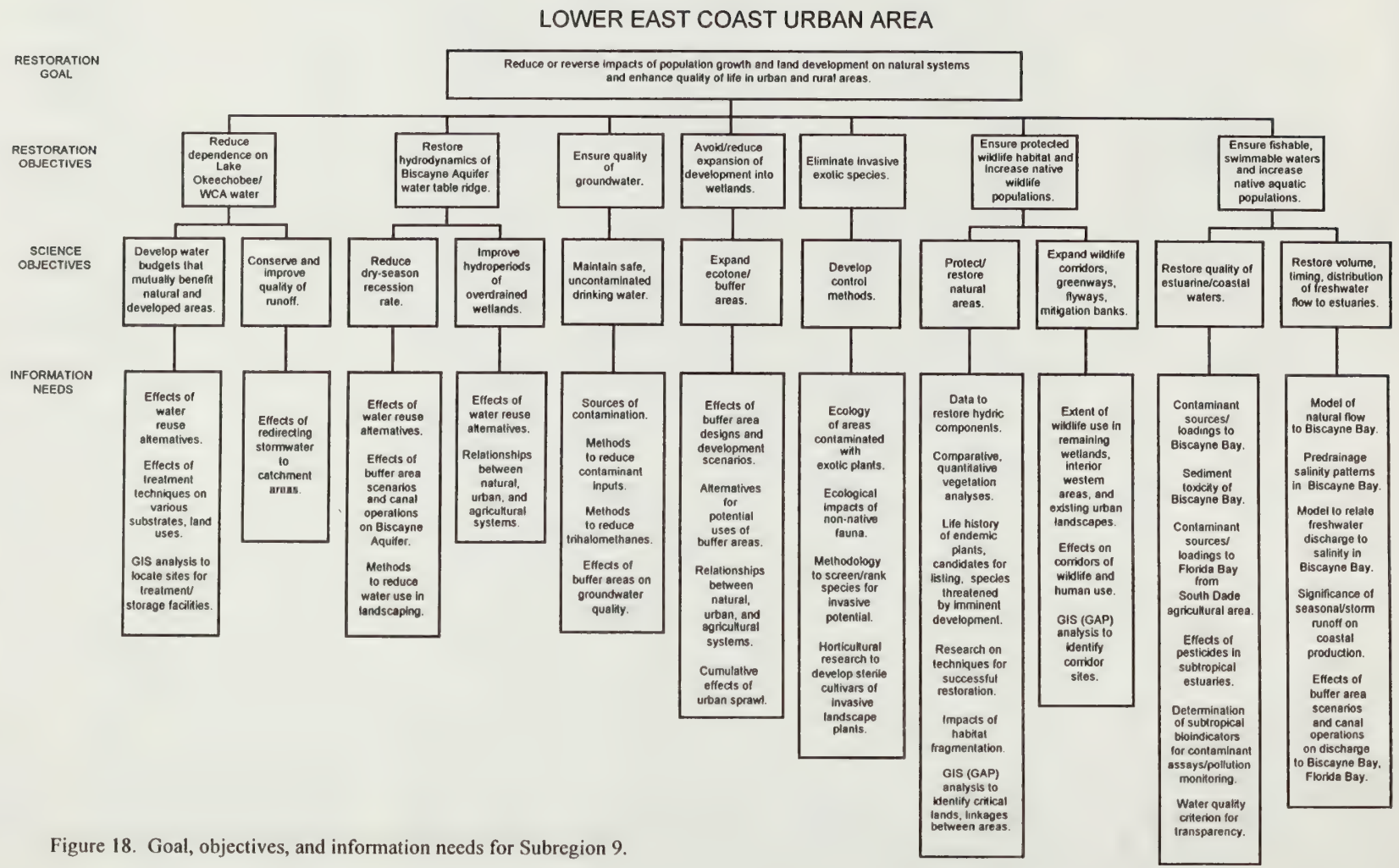

LOWER EAST COAST URBAN AREA
RESTORATION GOAL
Reduce or reverse impacts of population growth and land development on natural systems and enhance quality of life in urban and rural areas.
RESTORATION OBJECTIVES
Reduce dependence on Lake Okeechobee/ WCA water
Restore hydrodynamics of Biscayne Aquifer water table ridge.
Ensure quality of groundwater.
Avoid/reduce expansion of development into wetlands.
Eliminate invasive exotic species.
Ensure protected wildlife habitat and increase native wildlife populations.
Ensure fishable, swimmable waters and increase native aquatic populations.
SCIENCE OBJECTIVES
Develop water budgets that mutually benefit natural and developed areas.
Conserve and improve quality of runoff.
Reduce dry-season recession rate.
Improve hydroperiods of overdrained wetlands.
Maintain safe, uncontaminated drinking water.
Expand ecotone/ buffer areas.
Develop control methods.
Protect/ restore natural areas.
Expand wildlife corridors, greenways, flyways, mitigation banks.
Restore quality of estuarine/coastal waters.
Restore volume, timing, distribution of freshwater flow to estuaries.
INFORMATION NEEDS
Effects of water reuse alternatives.
Effects of treatment techniques on various substrates, land uses.
GIS analysis to locate sites for treatment/ storage facilities.
Effects of redirecting stormwater to catchment areas.
Effects of water reuse alternatives.
Effects of buffer area scenarios and canal operations on Biscayne Aquifer.
Methods to reduce water use in landscaping.
Effects of water reuse alternatives.
Relationships between natural, urban, and agricultural systems.
Sources of contamination.
Methods to reduce contaminant inputs.
Methods to reduce trihalomethanes.
Effects of buffer areas on groundwater quality.
Effects of buffer area designs and development scenarios.
Alternatives for potential uses of buffer areas.
Relationships between natural, urban, and agricultural systems.
Cumulative effects of urban sprawl.
Ecology of areas contaminated with exotic plants.
Ecological impacts of non-native fauna.
Methodology to screen/rank species for invasive potential.
Horticultural research to develop sterile cultivars of invasive landscape plants.
Data to restore hydric components.
Comparative, quantitative vegetation analyses.
Life history of endemic plants, candidates for listing, species threatened by imminent development.
Research on techniques for successful restoration.
Impacts of habitat fragmentation.
GIS (GAP) analysis to identify critical lands, linkages between areas.
Extent of wildlife use in remaining wetlands, interior western areas, and existing urban landscapes.
Effects on corridors of wildlife and human use.
GIS (GAP) analysis to identify corridor sites.
Contaminant sources/ loadings to Biscayne Bay.
Sediment toxicity of Biscayne Bay.
Contaminant sources/ loadings to Florida Bay from South Dade agricultural area.
Effects of pesticides in subtropical estuaries.
Determination of subtropical bioindicators for contaminant assays/pollution monitoring.
Water quality criterion for transparency.
Model of natural flow to Biscayne Bay.
Predrainage salinity patterns in Biscayne Bay.
Model to relate freshwater discharge to salinity in Biscayne Bay.
Significance of seasonal/storm runoff on coastal production.
Effects of buffer area scenarios and canal operations on discharge to Biscayne Bay, Florida Bay.

Figure 18. Goal, objectives, and information needs for Subregion 9.

Many activities related to ecosystem restoration issues have been carried out by municipal and county governments and local universities. These organizations possess an outstanding base of expertise crucial to implementation of restoration plans. Because of strong local efforts, science plans to support the above objectives must be coordinated with local governments, as well as environmental groups, to ensure: 1) the South Florida Ecosystem Restoration effort contributes to planned or ongoing restoration efforts by these organizations, 2) the South Florida Ecosystem Restoration effort results in direct environmental benefits to the LEC, and 3) planned or ongoing activities by these organizations contribute to and enhance the South Florida Ecosystem Restoration effort. The science recommendations for Subregion 9, as summarized in Figure 18 with their associated objectives, are outlined below.

Science Inventory

▸ Expand the inventory of scientific work completed, initiated, or planned in Subregion 9 that relates to and supports the South Florida Ecosystem Restoration effort.

- Identify lead agencies and individuals.
- Identify any additional projects needed to support efforts or to make efforts more beneficial to the overall restoration effort.
- Identify opportunities for local/Federal scientific interactions.

Critical Buffer Areas

▸ Conduct an interagency study, led by NBS GAP, to identify critical lands between the urban areas and the WCAs and ENP that must be preserved as buffer areas to support South Florida Ecosystem Restoration.

- Develop a digitized map with information layers in a GIS framework to establish area boundaries and investigate feasibility of land acquisition or other habitat protection measures.
- Evaluate criteria including habitat value of lands for Federally listed threatened and endangered species and State species of special concern (particularly replacement of short-hydroperiod wetlands needed by wading birds), present value for aquifer recharge, and potential usefulness for water reserves.
- Determine the potential effect on water supplies if the land were developed and the water table were lowered.

▸ Conduct a short-term, quantitative analysis, using the latest version of the South Florida Water Management Model, its Natural System Model corollary, and other analytical tools, to determine how various scenarios of future land use and associated local water use in the buffer areas will affect water supply and water management regimes required for ecosystem restoration.

- Determine cumulative effects of urban sprawl, including a range of full "worst case" to minimal residential and/or commercial development, into buffer wetlands.
- Evaluate potential use of these lands for stormwater treatment, aquifer recharge, wildlife support, and compatible low-impact recreational activities.

▸ Using the above information, evaluate interactions between natural, urban, and agricultural systems.

- Determine critical feedback linkages between the natural system and urban and agricultural systems.
- Determine the landscape configuration that will allow healthy natural systems and urban and agricultural systems to coexist.
- Determine how the natural system and its benefits to humans will be affected by different population levels and land use configurations.

Natural Areas and Corridors

► Provide scientific information to aid State and local efforts to identify and purchase or otherwise preserve (e.g., through incentives, easements) ecologically endangered lands, especially upland areas.

► Develop the scientific basis and standard procedures for successful restoration of natural areas. Many of these incorporate actions recommended in the restoration plan for the Dade County pine rocklands (Maguire 1995).

- Methods to determine appropriate siting conditions (e.g., soil contours, depth of saltwater/freshwater lens interface) for restoration/creation of wetlands.
- Methods to restore hydric components of pine rocklands and hammocks (e.g., pineland/prairie ecotones).
- Life history and reproduction of endemic plants of pine rocklands. This is especially important for assisting Dade County in restoration of Richmond Pineland Preserve, which inclu Federally owned land (U.S. Coast Guard, U.S. Customs, and U.S. Navy) in addition to l owned by Dade County PRD and UM.
- Life history and reproduction of endemic plants of scrub habitat.
- Efficient propagation techniques for native plants; e.g., seed germination.
- Establishment/maintenance of nurseries to provide plants for restoration.
- Optimum reforestation/revegetation strategies (e.g., to achieve uneven age structure in pinelands).
- Urban fire techniques appropriate for use in Subregion 9.
- Comparative, quantitative vegetation analyses of remaining hammocks to characterize and catalog them by species composition, species dominants, and spatial patterns of species distributions to provide information needed to guide management activities (e.g., to prevent degradation from nearby inappropriate landscape plantings).
- Effect of fragmentation on restored areas and of potential benefits of connectivity among restored areas and between them and proposed buffer areas.
- Methods to remove invasive plants from natural areas and to maintain control of invasives during restoration.

► Conduct GIS (GAP) analysis of urban and agricultural areas to develop scientific basis for siting effective wildlife corridors, flyways, and mitigation banks.

- Identify potential pathways for connecting remaining natural areas into a greenbelt/wildlife corridor and linking these to proposed buffer areas, using opportunities such as existing canal banks and railroad rights of way or undeveloped property in critical locations, even if disturbed.
- Identify wetland sites and their soils and history of land use (i.e., if farmed or not).
- Provide scientific information to aid development of comprehensive greenway plans and demonstration projects.

► Evaluate wildlife and human ecology effects of wildlife corridors.

- Determine effects of corridor size on wildlife movements.
- Determine effects of human use on wildlife corridors and greenways.

► Quantitatively evaluate wildlife use in remaining wetlands of southeast Dade County and in proposed buffer areas.

► Conduct an urban wildlife survey to compare wildlife support values of various existing landscapes within the urban setting for fauna such as resident, migrant, and wintering birds; herpetofauna such as lizards; and insects such as butterflies.

Protected Species

- Collect information needed for species that are potentially threatened or endangered, especially those threatened by imminent habitat loss in rapidly developing areas.

- Determine effects of estrogen-mimicking contaminants on reproduction of protected species

- Continue evaluation of manatee behavior and migration patterns in Biscayne Bay.

- Develop a science-based training course for certification of contractors bidding on COE construction projects that could affect species of environmental concern, including Federal and State-listed endangered and threatened species.

Quantity and Timing of Freshwater Flows to Estuaries

- Develop a model to estimate natural predrainage flows to Biscayne Bay.

- Estimate predrainage salinity patterns in Biscayne Bay by retrospective analyses of bottom sediments (i.e. foraminifera shells or diatom tests) and application of a natural system hydrologic model, refined and specially adapted to this use.

- Collect required field data to calibrate the relationship between stage and discharge in canals discharging to Biscayne Bay and other coastal waters of the LEC.

  - Recalculate historic flows based on the new calibration and existing time series of stage data.
  - Install continuous stage recording instruments in canals lacking this instrumentation.

- Map salinity patterns in Biscayne Bay under a range of freshwater inflow rates, and use this information to develop and calibrate a hydrodynamic model to relate freshwater discharges to salinity patterns in Biscayne Bay.

- Develop and apply a methodology to test various scenarios of buffer area utilization and associated canal operations for their effect on freshwater discharges to Biscayne Bay (adapt the SFWMM to this use).

  - Use this information to design a structural configuration and operational strategy that would reestablish a more natural seasonal pattern of freshwater flow to Biscayne Bay and Florida Bay.
  - Use output from the NSM and any available information relating freshwater flows to salinities for general guidelines concerning natural seasonal pattern in relation to rainfall.

Surface Water and Sediment Quality

- Provide the scientific basis for reevaluating and customizing existing water quality standards and monitoring to account for the unique chemistry of South Florida soils and waters and local practices associated with agricultural activities, lawn care and maintenance, aquatic weed control, golf course maintenance, local manufacturing, etc.

  - Determine if appropriate contaminants are being measured, given local application practices.
  - Determine if thresholds for environmental damage are appropriate for some pollutants, such as nitrogen and phosphorus, given natural concentrations of these constituents in local fresh and coastal waters.
  - Determine if thresholds for environmental damage are appropriate for contaminants such as heavy metals, PAHs, and synthetic organic chemicals given the relative low adsorbance characteristics of South Florida waters (i.e., low concentrations of clay particles and organics that bind heavy metals and organic chemicals and make them less available).
  - Evaluate use of biological indicators in water quality monitoring, since living organisms integrate biological effects of all stressors. Develop a suite of biological indicators for routine use and integrate biomonitoring with chemical analyses to determine ecological health.

- Evaluate use of an alternative (e.g., coliphage) to fecal coliform bacteria as an indicator of sewage-associated pathogens, given the rapid destruction of fecal coliforms in subtropical marine waters, and evaluate appropriateness of sewage contamination standards for LEC coastal waters.

▸ Determine concentrations and loadings of pollutants, including nutrients and contaminants, in canal discharges and direct (pipe) discharges to Biscayne Bay, Florida Bay, and other coastal water bodies.

- Identify hot spots, in terms of point source or nonpoint discharges of pollutants, including sewage.
- Compare pollutant concentrations of water entering the developed part of each county at the boundary of the WCAs and water exiting each county into coastal waters through the major canals (Miami; North New River; Hillsboro; West Palm Beach; and L-31N, which exits through C-111).
- Use the above information to determine total maximum daily loads and establish pollution load reduction goals in compliance with Federal (EPA) and State (FDEP) water quality standards.
- Determine significance of seasonal runoff and storms in controlling rates of production in coastal waters.

▸ Quantify applications of pesticides, herbicides, and other xenobiotic materials to residential and agricultural areas, golf courses, and public lands in Subregion 9.

▸ Determine concentration and distribution of estrogen-mimicking contaminants in surface waters.

▸ Determine effects on surface water and biota of pesticide and fertilizer applications on golf courses.

▸ Determine methods to reduce pesticide and herbicide applications to golf courses and other urban landscapes, including use of biological pest control agents and alternative landscape materials and designs.

▸ Conduct survey of sediment toxicity in Biscayne Bay.

▸ Determine biological effects of pollutants in subtropical estuaries.

- Identify tropical indicator organisms to use in toxicity testing.
- Examine increase in occurrence of cellular micronuclei observed with pollutant exposure.
- Develop toxicity and mutagenicity screening techniques to reduce expenses of sampling and chemical analyses.
- Determine relationship between water quality and benthic species ratios.

▸ Develop water quality criterion for transparency to protect benthic communities, such as seagrass.

▸ Evaluate water quality effects of redirecting stormwater runoff into buffer areas.

- Determine effects of urban stormwater on natural treatment areas.
- Determine effects of stormwater treatment on water quality of discharges to the Everglades, Florida Bay, and Biscayne Bay.
- Determine effects on water supply, wetlands, wildlife, and human health.

▸ Organize a contaminants committee to focus science efforts relative to contaminants, reduce redundancy in monitoring programs, achieve consistency in data collection protocols, and reduce pollutant loads at the local community level.

Groundwater Quality

▸ Identify sources of groundwater contamination.

▸ Develop methods to reduce inputs of contaminants to groundwater.

► Determine feasibility of using a water management approach compatible with the South Florida Ecosystem Restoration Program to reduce formation of trihalomethane precursors in raw water supplies.

- Estimate potential cost savings of implementing such an approach in contrast to a water treatment process.
- Further quantify potential improvements and savings through field experiments or pilot projects.

► Determine effects of buffer area scenarios on groundwater quality.

Water Consumption

► Determine effects of buffer area scenarios on groundwater recharge and water supply.

► Evaluate methods for reuse of treated wastewater.

- Develop pilot programs to investigate and demonstrate wastewater reuse on different substrates, including rockland sites, and particularly on golf courses, parks, and public facility grounds.
- Quantify potential benefits of water reuse to the future water supply of Subregion 9.
- Use GIS techniques to locate and quantify suitable lands and wastewater treatment facilities.
- Determine effects of wastewater reuse on groundwater and surface water quality.

► Develop methods for reduced water use on golf courses and other landscaping.

► Conduct a scientific survey of attitudes of homeowners, professional landscapers, and nurserymen to determine the most effective methods of promoting use of xeriscape landscaping with native plants. Non-native species suitable for xeriscaping are the same species most likely to become invasive in disturbed sites and natural areas; promotion of xeriscape landscaping with these plants will exacerbate the problem of invasive non-natives.

► Determine how local government ordinances promote or hinder use of native xeriscaping.

Invasive Nonindigenous Species

► Determine ecological effects of non-native fauna.

► Evaluate current ecological conditions of areas contaminated with invasive non-native plants.

► Develop sterile cultivars of popular landscape plants, such as poinciana and ornamental *Ficus*, that show tendencies to become invasive as their use increases and acreage and resultant seed bank of native species decrease.

► Develop a consistent, effective methodology for ranking non-native plant species for their invasive tendencies in the South Florida environment, starting with species on the FLEPPC list.

- Identify the greatest immediate threats as candidates for (1) major short-term, intensive, localized mechanical control efforts and (2) longer term biological control efforts. This will provide more lead time for developing environmentally safe, effective biological controls before each invasive species causes major damage to natural areas and wildlife habitat.

► Develop an effective, science-based approach to screen for potential invasive tendencies of plant materials 1) entering South Florida and 2) already in the landscape trade, but not yet observed outside cultivation.

Scientific Information Transfer

► Develop science-based information for use by the Public Information and Education Subgroup of the Working Group on South Florida Ecosystem Restoration.

BIBLIOGRAPHY

Adams, B.P., D.J. Sample, and L.C. Woehlcke. 1984. An evaluation of wastewater reuse policy options for the South Florida Water Management District. Technical Publication 84-6. SFWMD, West Palm Beach, Florida.

Alden, C.A. Undated. Greenway trail proposal, Goulds neighborhood redevelopment concept, Miami, Florida. Prepared for Metro-Dade Office of Community Development by Allen & Associates, P.A.

Alexander, T.R. 1958. Ecology of the Pompano Beach hammock. Quarterly Journal of the Florida Academy of Sciences 21:299-304.

Alexander, T.R. 1967a. A tropical hammock on the Miami (Florida) limestone -- a twenty-five-year study. Ecology 48:863-867.

Alexander, T.R. 1967b. Effect of Hurricane Betsy on the southeastern Everglades. Quarterly Journal of the Florida Academy of Sciences 30(1):10-24.

Alexander, T.R., and A.G. Crook. 1973. South Florida ecological study. Appendix G. Recent and long-term vegetation changes and patterns in South Florida. Part I. Preliminary report. PB-231 939. South Florida Environmental Project: Ecological Report No. DI-SFEP-74-08. DOI, Washington, D.C.

Alexander, T.R., and A.G. Crook. 1975. South Florida ecological study. Appendix G. Recent and long-term vegetation changes and patterns in South Florida. Part II. Final report. PB-231 939. South Florida Environmental Project: Ecological Report No. DI-SFEP-74-08. DOI, Washington, D.C.

Alexander, T.R., and A.G. Crook. 1984. Recent vegetational changes in southern Florida. Pages 199-210 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Alleman, R.W. Undated. Biscayne Bay: a survey of past mangrove mitigation/restoration efforts. Biscayne Bay Restoration and Enhancement Program. Metropolitan Dade County DERM, Miami, Florida.

Alleman, R.W. 1991. A synopsis of the water quality and monitoring program in Biscayne Bay, Florida. Pages 152-159 *in* W.J. Kenworthy, and E.E. Haunert, editors. The Light Requirements of Seagrasses: Proceedings of a Workshop to Examine the Capability of Water Quality Criteria, Standards and Monitoring Programs to Protect Seagrasses. NOAA Technical Memorandum NMFS-SEFC-287. NMFS, Beaufort, North Carolina.

Alleman, R.W. 1995. Progress of the Watershed Interactive Network Plan for South Dade County. Florida Scientist 58(Suppl.1):38 (Abstract).

Alleman, R.W., S.A. Bellmund, D.W. Black, S.A. Formati, C.A. Gove, and L.K. Gulick. 1995a. An update of the Surface Water Improvement and Management Plan for Biscayne Bay: Technical Supporting Document and Appendices. Planning Department, SFWMD, West Palm Beach, Florida.

Alleman, R.W., D.W. Black, S.E. Formati, L.K. Gulick, and J.A. VanArman. 1995b. An Update of the Surface Water Improvement and Management Plan for Biscayne Bay: Planning Document. Planning Department, SFWMD, West Palm Beach, Florida.

Alleman, R., T. Singleton, D. Williams, and M. Brown. Undated. South Dade Watershed Project WIN Plan, Watershed Interactive Network. Information paper. SFWMD and UM Center for Urban & Community Design.

Allman, D.W., P.G. Jakob; and T. McCann. 1979. Improvement of the canal-aquifer flow regime in the C-1N basin. Resource Planning Department, SFWMD, West Palm Beach, Florida.

Alvarez, J.A., and D.D. Bacon. 1988. Production zones of major public water supply wellfields for the counties in the South Florida Water Management District. Technical Publication 88-4 and Appendix II. SFWMD, West Palm Beach, Florida.

Anderson, S.D. 1986. South Dade agricultural pilot study. Technical Memorandum DRE-219. SFWMD, West Palm Beach, Florida.

Anderson, S.D., and J.E. Shaw. 1991. East Everglades ground water quality monitoring study, 1985-1986. Technical Memorandum DRE-303. SFWMD, West Palm Beach, Florida.

Area Planning Board of Palm Beach County. 1974. Stormwater study design. Area Planning Board, West Palm Beach, Florida.

Ault, J.S., J.E. Serafy, M.E. Clarke, and P.B. Ortner. 1995. Biscayne Bay Red Drum Enhancement Program fishery-independent assessment. First annual report to FDEP, contract MR018. RSMAS, Miami, Florida.

Austin, D.F. 1976. Vegetation of southeastern Florida - I. Pine Jog. Florida Scientist 39:230-235.

Austin, D.F., K. Coleman-Marois, and D.R. Richardson. 1977. Vegetation of southeastern Florida - II-V. Florida Scientist 40:331-361.

Austin, D.F., F.R. Posin, and J.N. Burch. 1987. Scrub species patterns on the Atlantic Coastal Ridge, Florida. Journal of Coastal Research 3:491-498.

Austin, D.F., and J.G. Weise. 1972. Annotated checklist of the Boynton Beach Hammock. Quarterly Journal of the Florida Academy of Sciences 35:145-154.

Avino, J.G. 1993. Resolution authorizing the disbursement of funds from the Dade County Tree Trust Fund for the development of a comprehensive forest management plan for the Richmond pinelands. Resolution No. R-745-93. Dade County Board of Commissioners, Florida.

Baker, J. 1988. Survey of chlorinated pesticide residues in groundwater in rural areas of Dade County. Environmental Monitoring Division, Dade County DERM, Miami, Florida.

Ball, M.C. 1980. Patterns of secondary succession in a mangrove forest of southern Florida. Oecologia 44:226-235.

Bayer, F.M. 1948. Charles T. Simpson's types in the molluscan genus *Liguus*. Smithsonian Miscellaneous Collections 107(16):1-9.

Bentzien, M.M. 1987. Agency draft recovery plan for five pine rockland plant species. FWS, Atlanta, Georgia.

Biggs, J.E., and K.D. Saari. 1995. Effective use of a Geographic Information System in a design workshop. Florida Scientist 58(Suppl.1):35 (Abstract).

Biological & Environmental Consulting, Inc. 1995. Phase I: Biological inventory of coastal hammock site on Virginia Key, Florida. Prepared for Department of Development, City of Miami.

Birnhak, B.I. 1974. An examination of the influence of freshwater canal discharges on salinity in selected southeastern Florida estuaries. PB-231 610. South Florida Environmental Project: Ecological Report No. DI-SFEP-74-19. DOI, Washington, D.C.

Birnhak, B.I., and J.P. Crowder. 1974. An evaluation of the extent of vegetative habitat alteration in south Florida 1943-1970. PB-231 621. South Florida Environmental Project: Ecological Report No. DI-SFEP-74-22. DOI, Washington, D.C.

Biscayne Bay Management Committee. Undated(a). State of the Bay. Special guide to Biscayne Bay 1989-90. Biscayne Bay Management Committee, Miami, Florida.

Biscayne Bay Management Committee. Undated(b). State of the Bay 1991-1992. Annual report of the Biscayne Bay Management Committee and a special guide to Biscayne Bay. Biscayne Bay Management Committee, Miami, Florida.

Blair, S.M., T.L. McIntosh, and B.J. Mostkoff. 1994. Impacts of Hurricane Andrew on the offshore reef systems of central and northern Dade County, Florida. Bulletin of Marine Science 54(3):961-973.

Blom, E. 1994. An airport with a heart. Bird Watcher's Digest 16(4):12.

Bohnsack, J.A., and F.J. Mazzotti. 1975. Mangrove forest transect, Caloosa [*sic*] Park, Key Biscayne, Florida. Pages 1-10 *in* L.P. Thomas, compiler. Shallow-Water Marine Environments of the Caribbean. A collection of reports done by students in MBS 675. RSMAS, Miami, Florida.

Broadwell, A.L. 1992. Effects of beach renourishment on the survival of loggerhead sea turtle nests. Pages 21-23 *in* M. Salmon and J. Wyneken, editors. Proceedings of the Eleventh Annual Workshop on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-302. NMFS, Miami, Florida.

Broward County Board of Commissioners. 1989a. 1989 Land Use Plan. Plus text amendments and maps. Broward County, Florida, Comprehensive Plan, plus maps. Broward County Planning Council, Fort Lauderdale.

Broward County Board of Commissioners. 1989b. Broward County, Florida, Comprehensive Plan 1989. Volume 3, support documents, March 1, 1989. Broward County Planning Council, Fort Lauderdale.

Broward County Board of Commissioners. 1993a. Broward County, Florida, Comprehensive Plan 1989. Volume 2, adopted components, as amended through December 10, 1993. Broward County Planning Council, Fort Lauderdale.

Broward County Board of Commissioners. 1993b. Broward County, Florida, Comprehensive Plan 1989. Volume 4, support documents, as amended through December 10, 1993. Broward County Planning Council, Fort Lauderdale.

Broward County Department of Natural Resource Protection. 1993. New River study: final report. Technical Report Series TR:93-06. Broward County DNRP, Fort Lauderdale, Florida.

Broward County Parks and Recreation Division. Undated(a). Fact sheets on ESL sites. Broward County Community Services Department, PRD, Oakland Park, Florida.

Broward County Parks and Recreation Division. Undated(b). Resource management for 1989 Environmentally Sensitive Lands Bond Issue sites. Broward County Community Services Department, PRD, Oakland Park, Florida.

Broward County Parks and Recreation Division. 1989. West Lake Mitigation Program. Fact sheet. Public Service Department, Broward County PRD, Oakland Park, Florida.

Broward County Parks and Recreation Division. 1992a. Fern Forest Nature Center. Brochure. Broward County Community Services Department, PRD, Oakland Park, Florida.

Broward County Parks and Recreation Division. 1992b. Secret Woods Nature Center. Brochure. Broward County Community Services Department, PRD, Oakland Park, Florida.

Broward County Parks and Recreation Division. 1992c. Deerfield Island Park. Brochure. Broward County Community Services Department, PRD, Oakland Park, Florida.

Broward County Parks and Recreation Division. 1992d. Tree Tops Marsh Restoration Project: an overview. Interpretive Section, PRD, Oakland Park, Florida

Broward County Parks and Recreation Division. 1993. Environmentally Sensitive Lands Bond Program, Broward County, Florida - March 1989. Map and table, 10/27/93, as revised. Environmental Section, PRD, Oakland Park, Florida

Broward County Planning Council. 1989a. Beaches, rivers, harbors, drainage canals, major lakes & estuarine system. Broward County Land Use Plan, Natural Resource Map Series, sheet 8. BCPC, Fort Lauderdale, Florida.

Broward County Planning Council. 1989b. Flood plains & flood prone areas. Broward County Land Use Plan, Natural Resource Map Series, sheet 6. BCPC, Fort Lauderdale, Florida.

Broward County Planning Council. 1991. Generalized wetlands, southwestern Broward County. Broward County Land Use Plan, Natural Resource Map Series, sheet 10. BCPC, Fort Lauderdale, Florida.

Browder, J.A. 1991. Watershed management and the importance of freshwater flow to estuaries. Pages 7-22 *in* S.F. Treat and P.A. Clark, editors. Proceedings, Tampa Bay Area Scientific Information Symposium (BASIS) 2 -The Watershed. TEXT, Tampa, Florida.

Browder, J.A., C. Littlejohn, and D. Young. Undated. The South Florida Study, South Florida: Seeking a Balance of Man and Nature. UF Center for Wetlands and Florida Bureau of Comprehensive Planning.

Browder, J.A., D.B. McClellan, D.E. Harper, M.G. Kandrashoff, and W. Kandrashoff. 1993. A major developmental defect observed in several Biscayne Bay, Florida, fish species. Environmental Biology of Fishes 37:181-188.

Browder, J.A., and P.B. Schroeder. 1980. Melaleuca seed dispersal and perspectives on control. Pages 17-21 *in* R.K. Geiger, compiler. Proceedings of *Melaleuca* Symposium, September 23-24, 1980. FDACS, FDOF, Tallahassee, Florida.

Brown, R.H., and G.G. Parker. 1945. Salt water encroachment in limestone at Silver Bluff, Miami, Florida. Economic Geology 40(4):235-262.

Buchanan, T.J., and H. Klein. 1976. Effects of water management on fresh-water discharge to Biscayne Bay. Pages 271-277 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Burch, J.N., and G.A. Marsh. 1987. Survey of natural resources within the limits of the Florida Atlantic University campus. Joint Center for Environmental and Urban Problems, FAU, Boca Raton, Florida.

Bureau of Economic and Business Research, College of Business Administration, University of Florida. 1994. 1994 Florida Statistical Abstract. University Press of Florida, Gainesville, Florida.

Burney, C.M. 1994. Sea turtle nesting and its management in Broward County. Page 29 *in* C.N.K. Mooers, convenor. Florida Coastal Ocean Sciences Symposium, 21 and 22 April 1994. Ocean Pollution Research Center, RSMAS, Miami, Florida.

Burney, C., B.J. Baca, G.S. Kleppel, et al. 1991. An analysis of the 20-year use of a deep Broward County limerock pit as a natural advanced wastewater treatment and groundwater recycling facility. Special report. Joint Center for Environmental and Urban Problems, FAU/FIU, Fort Lauderdale, Florida.

Burney, C., and W. Margolis. 1993. Sea Turtle Conservation Program, Broward County, Florida, 1993 report. Technical Report 93-10. Broward County DNRP, Biological Resources Division, Fort Lauderdale, Florida.

Burney, C., and C. Mattison. Undated. Sea Turtle Conservation Project, Broward County, Florida, 1991 report. Broward County Office of Natural Resource Protection, Erosion Prevention District, Fort Lauderdale, Florida.

Burney, C., and C. Mattison. 1993. Sea Turtle Conservation Program, Broward County, Florida, 1992 report. Technical Report 93-1. Broward County DNRP, Biological Resources Division, Fort Lauderdale, Florida.

Burney, C.M., C. Mattison, and L. Fisher. 1990. The relationship of loggerhead nesting patterns and moon phase in Broward County, Florida. Pages 161-164 *in* T.H. Richardson, J.I. Richardson, M. Donnelly, editors. Proceedings of the Tenth Annual Workshop on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFC-278. NMFS, Miami, Florida.

Burns, S., C. Cassagnol, P. Millar, D. Nealon, R. Santee, P. Trimble, and P. Walker. 1982. Southwest Broward County study. Technical Memorandum DRE-145. SFWMD, West Palm Beach, Florida.

Burns & McDonnell. 1994. Everglades Protection Project, Palm Beach County, Florida, conceptual design. Burns & McDonnell, Kansas City, Missouri.

Burzycki, G. 1994a. Letter to C. Goodyear, February 22, 1994. Metro-Dade DERM, Miami, Florida.

Burzycki, G. 1994b. Bulk Carrier site restoration. Presentation to Dade Chapter, Florida Native Plant Society, April 26, 1994.

Burzycki, G.M., and D.L. Drum. 1992. Technical summary document, environmental/regulatory planning for the SW Biscayne Bay wetlands (Advance Identification of Disposal areas). Final draft. Metro-Dade DERM, Miami, Florida.

Cantillo, A.Y., T.P. O'Connor, and G.G. Lauenstein. 1993. South Florida environmental quality. NOAA Technical Memorandum NOS ORCA 75. NOAA, Silver Spring, Maryland.

Capo, T.R., and B.B. Wisner. 1995. Biscayne Bay Stock Enhancement Program: grow-out, tagging, and release. Final report, DEP contract number MR014. Experimental Hatchery, RSMAS, Miami, Florida.

Center for Marine and Environmental Analyses. 1995. Task statements for Ecological Risk Assessment and Ecosystem Management Program. CMEA, RSMAS, Miami, Florida.

Central and Southern Florida Flood Control District. 1973. Preliminary evaluation report on land and water management planning in the C-51 watershed. C&SF FCD, West Palm Beach, Florida, for Division of State Planning, State Department of Administration.

Central and Southern Florida Flood Control District. 1974. Response to U.S. Corp [*sic*] of Engineers draft survey review report on the Hillsboro Canal Basin. C&SF FCD, West Palm Beach, Florida.

Central and Southern Florida Flood Control District. 1976. Water management plan for the western C-9 basin. C&SF FCD, West Palm Beach, Florida, for South Florida Regional Planning Council.

Central and Southern Florida Flood Control District and the Dade County Metropolitan Government. 1959. A report on Area B Dade and Broward counties, a part of the Central and Southern Florida Flood Control District. C&SF FCD, West Palm Beach, Florida.

CH2M Hill. 1994. Analysis of water supply potential for Area B, the Everglades Buffer Strip, and the Hillsboro Basin: Phase 3b East Coast Buffer implementation (C-4123-A3). Draft. Prepared for SFWMD, West Palm Beach, Florida.

City of Boca Raton. 1991. Environmentally Sensitive Lands Referendum, October 22, 1991. Information sheet, list, map, and descriptions of sites. City of Boca Raton, Boca Raton, Florida.

City of Miami. 1992. Miami River Master Plan. Final report - January, 1992. City of Miami, Department of Planning, Building and Zoning, Miami, Florida.

City of Miami. 1987. Virginia Key Master Plan. City of Miami Planning Department, Miami, Florida.

Clench, W.J. 1946. A catalogue of the genus *Liguus* with a description of a new subgenus. Occasional Papers on Mollusks 1(10):117-128.

Coastal Technology Corporation. Undated. Filling program for dredged depressions in north Biscayne Bay. Metro-Dade DERM Technical Report 89-10. Metropolitan Dade County DERM, Miami, Florida.

Coile, N.C. 1993. Florida's endangered and threatened plants. Contribution No. 29, Bureau of Entomology, Nematology and Plant Pathology - Botany Section. FDACS, Division of Plant Industry, Gainesville, Florida.

Committee to Review the USGS National Water Quality Assessment Pilot Program. 1990. A review of the USGS National Water Quality Assessment Pilot Program. National Academy Press, Washington, D.C.

Conley, W.J., and B.A. Hoffman. 1987. Nesting activity of sea turtles in Florida, 1979-1985. Florida Scientist 50:201-210.

Consiglio, B., and G. Reynolds. 1987. Broward's burrowing owl watchers. Florida Naturalist, Spring 1987:3-5.

Cantillo, A.Y., T.P. O'Connor, and G.G. Lauenstein. 1993. South Florida environmental quality. NOAA Technical Memorandum NOS ORCA 75. NOAA, Silver Spring, Maryland.

Cooper, R.M., and J. Lane. 1987a. An atlas of eastern Broward County surface water management basins. Technical Memorandum DRE-231. SFWMD, West Palm Beach, Florida.

Cooper, R.M., and J. Lane. 1987b. An atlas of eastern Dade County surface water management basins. Technical Memorandum DRE-239. SFWMD, West Palm Beach, Florida.

Cooper, R.M., and J. Lane. 1988. An atlas of eastern Palm Beach County surface water management basins. Technical Memorandum DRE-244. SFWMD, West Palm Beach, Florida.

Cooperative Extension Service. Undated. Exotic invaders of the Everglades. UF, IFAS.

Corcoran, E.F., M.S. Brown, and A.D. Freay. 1987. Organic pollution of the water in the Black Creek vicinity, Biscayne National Park. Research/Resources Management Report SER-86. NPS, Southeast Regional Office, Atlanta, Georgia.

Cotleur Hearing. 1995. Florida Power & Light Company South Dade Mitigation Bank. April 1995 report. Cotleur Hearing, Inc., Jupiter, Florida.

Courtenay, W.R. Jr. 1994a. Non-indigenous fishes in Florida. Pages 57-63 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Courtenay, W.R. Jr. 1994b. Current major pathways of fish introductions. Pages 64-66 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Courtenay, W.R. Jr., and D.A. Hensley. 1979. Range expansion in southern Florida of the introduced spotted tilapia, with comments on its environmental impress. Environmental Conservation 6(2):149-151.

Cox, J. 1987. The breeding bird survey in Florida: 1969-1983. Florida Field Naturalist 15:29-44.

Cox, J., D. Inkley, and R. Kautz. 1987. Ecology and habitat protection needs of gopher tortoise (*Gopherus polyphemus*) populations found on lands slated for large-scale development in Florida. Nongame Wildlife Program Technical Report Number 4. FGFWFC, Tallahassee, Florida.

Cox, J., R. Kautz, M. MacLaughlin, and T. Gilbert. 1994. Closing the Gaps in Florida's Wildlife Habitat Conservation System. Office of Environmental Services, FGFWFC, Tallahassee, Florida.

Craig, A.K. 1973. A new record for *Liguus*: the Boynton Beach colony. The Nautilus 87(3):83-85.

Craig, A.K. 1991. The physical environment of South Florida. Pages 1-16 *in* T.D. Boswell, editor. South Florida: The Winds of Change. Annual Conference, Association of American Geographers, Miami, Florida.

Craighead, F.C., Sr. 1984. Hammocks of South Florida. Pages 191-198 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Cullum, M.G. 1984. Evaluation of the water management system at a single family residential site: water quality analysis for selected storm events at Timbercreek subdivision in Boca Raton, Florida. Technical Publication 84-11, Volume II. SFWMD, West Palm Beach, Florida.

Dade County Department of Environmental Resources Management. Undated(a). A data summary of the 1987-1991 Biscayne Bay and tributaries surface water quality monitoring program. Draft. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. Undated(b). Computerized pineland and hammock forest inventory for Dade County. Draft project description, Hurricane Andrew urban reforestation grant application. DERM, Upland Planning Program, Miami, Florida.

Dade County Department of Environmental Resources Management. Undated(c). Environmentally Endangered Lands (EEL) Covenant information. Fact sheet. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. Undated(d). Genetic profile of South Florida slash pine. Draft project description. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. Undated(e). Pesticides used in West Wellfield study area 1988. West Wellfield Subcommittee on Agriculture, DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. Undated(f). Scope of work 2.0. Wetland restoration plan for the National Bulk Carrier's site. Pages 4-5, Exhibit "A" - C-3259-A1, and maps. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. Undated(g). South Dade wetlands vegetation mapping statement of work. Draft. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. Undated(h). The Biscayne Bay Surface Water Quality Monitoring Program (BBSWQMP): Recommendations based on the July 1991 to June 1992 data. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1990a. Agricultural and agrichemical-related operations within the West Wellfield Interim Protection Area: I. General introduction and description of potential point sources of water pollution. Report to the West Wellfield Policy Advisory Committee. June 25, 1990. Planning and Evaluation Section, DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1990b. Agricultural and agrichemical-related operations within the West Wellfield Interim Protection Area: II. Existing regulations and options to control potential pollution point sources. Report to the West Wellfield Policy Advisory Committee. July 30, 1990. Planning and Evaluation Section, DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1991. Agricultural and agrichemical-related operations in wellfield protection areas: II. Introduction to potential non-point sources of water pollution. Draft Report to the West Wellfield Technical Advisory Committee. March 5, 1991. Planning and Evaluation Section, DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1992a. Issues regarding pesticide, fertilizer and soil amendment use within the West Wellfield Interim Protection Area. Report to the West Wellfield Technical Advisory Committee. July 7, 1992. Planning and Evaluation Section, DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1992b. Save Our Rivers/Model Land site. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1993a. Endangered pine rockland plant species recovery project. Draft annual report. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1993b. Miami River Water Quality Plan. A report submitted to: The Miami River Water quality Commission, and Appendices B through H. Metro Dade DERM Technical Report 93-3. DERM, Natural Resources Division, Miami, Florida.

Dade County Department of Environmental Resources Management. 1993c. Model Lands Addition. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1993d. Status report on environmental studies. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1994a. Dade County Manatee Protection Plan. Partially revised second draft. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1994b. Dade County pine rockland restoration plan following Hurricane Andrew. Draft document. DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1994c. Progress report for October-December 1993. Wetland restoration plan for the National Bulk Carrier's site (#C-3259-A1, Scope of Work 2.0). DERM, Miami, Florida.

Dade County Department of Environmental Resources Management. 1994d. DERM goes fishing in Dade County canals. Environmental Impact 1(4). DERM, Miami, Florida.

Dade County Park and Recreation Department. Undated(a). Exotic pest plant control survey instructions. PRD, Natural Areas Management, Miami, Florida.

Dade County Park and Recreation Department. Undated(b). Post-hurricane natural areas recovery program. Executive summary. PRD, Natural Areas Management, Miami, Florida.

Dade County Park and Recreation Department. 1991. Crandon Park, Natural Areas Protection Plan. PRD, The Nature Conservancy, and Fairchild Tropical Garden, Miami, Florida.

Dade County Park and Recreation Department. 1994a. Post-hurricane pineland restoration program. Executive summary. PRD, Natural Areas Management, Miami, Florida.

Dade County Park and Recreation Department. 1994b. Dade County pine rocklands. Information sheet. PRD, Natural Areas Management, Miami, Florida.

Dade County Park and Recreation Department. 1994c. Fire! Information sheet. PRD, Natural Areas Management, Miami, Florida.

Daigle, J.J. 1984. New county records for *Crocothemis servilla* (Dru.) from Florida, United States (Anisoptera: Libellulidae). Notul. odonatol. 2(4):53-72.

Dalrymple, G.H. 1994. Non-indigenous amphibians and reptiles in Florida. Pages 67-78 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Dalrymple, N.K., G.H. Dalrymple, and K.A. Fanning. 1993. Vegetation of restored rock-plowed wetlands of the East Everglades. Restoration Ecology 1(4):220-225.

Danhausen, K. 1994. Letter to C. Goodyear, June 12, 1994. Summary of wetland restoration projects. Metro Dade Department of Solid Waste Management, Miami Florida.

Davis, J.H. Jr. 1943. The natural features of southern Florida, especially the vegetation, and the Everglades. Geological Bulletin No. 25. Florida Geological Survey, Tallahassee, Florida.

Department of the Interior. 1973. Resource and land information for South Dade County, Florida. Geological Survey Investigation I-850. USGS, Reston, Virginia.

Department of the Interior. 1994. The Impact of Federal Programs on Wetlands. Volume II. A report to Congress by the Secretary of the Interior. DOI, Washington, D.C.

de Sylva, D.P. 1976. Fishes of Biscayne Bay, Florida. Pages 181-202 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Doren, R.F., G. Molnar, and D. Sylvia. 1990. Restoration of former wetlands within the Hole-in-the-Donut in Everglades National Park. Pages 33-50 *in* F.J. Webb Jr., editor. Proceedings of the Seventeenth Annual Conference on Wetlands Restoration and Creation. Hillsborough Community College, Plant City, Florida.

Doren, R.F., W.J. Platt, and L.D. Whiteaker. 1993. Density and size structure of slash pine stands in the everglades region of south Florida. Forest Ecology and Management 59:295-311.

Drum, D.L. 1993. Issues of sustainability and habitat fragmentation in land acquisition programs: a Dade County perspective. Master's thesis. UM, Coral Gables, Florida.

Duda, M.D. 1987. Floridians and wildlife, sociological implications for wildlife conservation in Florida. Nongame Wildlife Program Technical Report No. 2. FGFWFC, Tallahassee, Florida.

Duquesnel, J. 1994a. Exotic tortoise beetle on *Ipomoea* sp. The Palmetto 1994 (Summer):17-18. The Florida Native Plant Society, Orlando, Florida.

Duquesnel, J. 1994b. Exotic weevil on bromeliads. The Palmetto 1994 (Summer):17. The Florida Native Plant Society, Orlando, Florida.

Egler, F.E. 1952. Southeast saline Everglades vegetation, Florida, and its management. Vegetatio Acta Geobotanica 3:213-265.

Ellis, T.M. 1980. *Caiman crocodilus*: an established exotic in South Florida. Copeia 1980:152-154.

Emmel, T.C. 1992. Mother Nature reeks havoc on endangered habitats. The Florida Naturalist 65(3):12-13,15,22.

Emmel, T.C., and R. Boender. 1991. Wings in paradise: Florida's Butterfly World. Wings(Winter 1991):7-12.

Enge, K.M. 1991. Herptile exploitation. Annual Performance Report, 1 July 1990 - 1 July 1991. Bureau of Nongame Wildlife, Division of Wildlife, FGFWFC, Tallahassee, Florida.

Environmental Protection Agency. 1982. Superfund record of decision: Miami Drum Services site, FL. EPA/ROD/R04-82/001. EPA, Washington, D.C.

Environmental Protection Agency. 1985a. Superfund record of decision: Davie Landfill, FL. EPA/ROD/R04-85/005. EPA, Washington, D.C.

Environmental Protection Agency. 1985b. Superfund record of decision: Varsol spill site, FL. EPA/ROD/R04-85/002. EPA, Washington, D.C.

Environmental Protection Agency. 1985c. Superfund record of decision: Biscayne Aquifer sites, FL. EPA/ROD/R04-85/004. EPA, Washington, D.C.

Environmental Protection Agency. 1986. Superfund record of decision: Pepper's Steel, FL. EPA/ROD/R04-86/008. EPA, Washington, D.C.

Environmental Protection Agency. 1987a. Superfund record of decision: NW 58th St., L.F., FL. EPA/ROD/R04-87/027. EPA, Washington, D.C.

Environmental Protection Agency. 1987b. Superfund record of decision: Gold Coast, FL. EPA/ROD/R04-87/028. EPA, Washington, D.C.

Environmental Protection Agency. 1990a. EPA selects remedy to abate environmental threat at Munisport Superfund site, Miami, Florida. News release. EPA, Region 4, Atlanta, Georgia.

Environmental Protection Agency. 1990b. Munisport Landfill public meeting at Florida International University re: National Priorities List site. March 29, 1990. Transcript.

Environmental Protection Agency. 1990c. Superfund record of decision: Munisport Landfill, FL. EPA/ROD/R04-90/062. EPA, Washington, D.C.

Environmental Protection Agency. 1990d. Superfund record of decision: Petroleum Products, FL. EPA/ROD/R04-91/079. EPA, Washington, D.C.

Environmental Protection Agency. 1992. Advance Identification of Wetlands Program. Fact sheet. EPA, Region 4, Atlanta, Georgia.

Environmental Protection Agency. 1993. EPA at work...protecting South Florida: Federal efforts to manage hazardous and solid waste in South Florida. EPA-904-F-93-001. Waste Management Division, EPA, Region 4, Atlanta, Georgia.

Environmental Protection Agency. 1994a. South Florida wetland planning activities, advance identification (ADID) wetland planning projects. Wetlands Planning Unit, EPA, Region 4, Atlanta, Georgia.

Environmental Protection Agency. 1994b. Superfund fact sheet, explanation of significant differences, Munisport Landfill Superfund Site, North Miami, Florida. EPA, Region 4, South Superfund Remedial Branch, Atlanta, Georgia.

Environmental Protection Agency. 1994c. Superfund update, Munisport Landfill. Superfund Volume 1, No. 4. EPA, Region 4, Munisport Project, Oak Ridge, Tennessee.

Environmental Protection Agency. 1994d. EPA Superfund record of decision: Davie Landfill site, Davie, FL, 8/11/1994, summary of remedial alternative selection. EPA/ROD/R04-94/180. EPA, Region IV, Atlanta, Georgia.

Environmental Protection Agency. 1995. South Florida atmospheric mercury monitoring pilot study research plan. EPA, Region IV, Atlanta, Georgia.

Evoy, J., and R. Schechtman. 1986. Biscayne Bay Aquatic Preserve Management Plan. Draft. Metro-Dade Planning Department, Miami, Florida.

Federal Aviation Administration. 1994. Project specifications, environmental restoration of the H/DME site on NOAA property, Virginia Key, Miami, Florida. Phase 1: Earthwork and Phase 2: Planting. FAA-SO-1188, January 26, 1994, and modifications to drawings and specifications, March 16, 1994. DOT, FAA, Southern Region, Atlanta, Georgia.

Federal Highway Administration and Florida Department of Transportation. 1992. Final environmental impact statement. FHWA-FLA-EIS-90-01-F. FDOT, Region Four, Miami, Florida.

Federal Water Quality Administration. 1970. Pollution of the waters of Dade County, Florida. DOI, FWQA, Southeast Water Laboratory, Lower Florida Estuary Study, Fort Lauderdale, Florida.

Fell, J.W., R.C. Cefalu, I.M. Master, and A.S. Tallman. 1975. Microbial activities in the mangrove (*Rhizophora mangle*) leaf detrital system. Pages 661-679 *in* G.E. Walsh, S.C. Snedaker, and H.J. Teas, editors. Proceedings of the International Symposium on Biology and Management of Mangroves. Volume II. IFAS, UF, Gainesville, Florida.

Fell, J.W., and I.M. Master. 1973. Fungi associated with the degradation of mangrove (*Rhizophora mangle* L.) leaves in South Florida. Pages 455-465 *in* L.H. Stevenson and R.R. Colwell, editors. Estuarine Microbial Ecology. University of South Carolina Press, Columbia, South Carolina.

Fernald, R.T. 1989. Coastal xeric scrub communities of the Treasure Coast Region, Florida: a summary of their distribution and ecology, with guidelines for their preservation and management. Nongame Wildlife Program Technical Report No. 6. FGFWFC, Tallahassee, Florida.

Fernald, R.T., and B.R. Toland. 1991. The Florida scrub jay. Pamphlet. Office of Environmental Services and Office of Informational Services, FGFWFC, Tallahassee, Florida.

Ferrell, D.L. 1994. Letter to Col T.L. Rice, District Engineer, Corps of Engineers, from Field Supervisor, Fish and Wildlife Service. November 18, 1994. FWS, Vero Beach, Florida.

Ferrell, M.M. 1993. A feasibility study for ecotourism development: a Metro-Dade County venture. Master's thesis. UM, Coral Gables, Florida.

Fish, J.E., and M. Stewart. 1991. Hydrogeology of the surficial aquifer system, Dade County, Florida. Water-Resources Investigations Report 90-4108. USGS, Tallahassee, Florida.

Fish and Wildlife Service. 1980a. 1:250,000-scale map of Atlantic Coast ecological inventory, Miami, Florida. 25080-A1-E1-250. USGS, Reston, Virginia.

Fish and Wildlife Service. 1980b. 1:250,000-scale map of Atlantic Coast ecological inventory, West Palm Beach, Florida. 26080-A1-E1-250. USGS, Reston, Virginia.

Fish and Wildlife Service. 1990. Endangered and threatened Species Recovery Program. Report to Congress. Superintendent of Documents, Washington, D.C.

Fish and Wildlife Service. 1993. Endangered and Threatened Wildlife and Plants. 50 CFR 17.11 & 17.12. August 23, 1993. GPO, Washington, D.C.

Fish and Wildlife Service. 1994. Lists of federally listed threatened and endangered species and category 1 and 2 candidates for federal listing in Palm Beach County, Broward County, and Dade County. FWS, Vero Beach, Florida.

Fisher, J.B. 1994. Biological monitoring project. Garden News 49(2):36. Fairchild Tropical Garden, Miami, Florida.

Fisk, E.J. 1975. Least tern: beleagured [*sic*], opportunistic and roof-nesting. American Birds 29(1):15-16.

Fisk, G. 1995. Impacts of expansion at Port Everglades: a case study of environmental mitigation. Pages 9-30 *in* D. Suman, M. Shivlani, and M. Villanueva, editors. Urban Growth and Sustainable Habitats: Case Studies of Policy Conflicts in South Florida's Coastal Environment. Division of Marine Affairs and Policy, RSMAS, Miami, Florida.

Fitzpatrick, J.W., G.E. Woolfenden, and M.T. Kopeny. 1991. Ecology and development-related habitat requirements of the Florida scrub jay (*Aphelocoma coerulescens coerulescens*). Nongame Wildlife Program Technical Report No. 8. Office of Environmental Services, FGFWFC, Tallahassee, Florida.

Fletemeyer, J. 1977. Coastwatch, Florida. Underwater Naturalist 10(4):26-27.

Fletemeyer, J. 1983. 1983 report, sea turtle monitoring project. Cooperative Sea Turtle Monitoring Program, Nova University and Broward County Environmental Quality Control Board.

Fletemeyer, J. 1984. 1984 report, sea turtle monitoring project. Cooperative Sea Turtle Monitoring Program, Nova University and Broward County Environmental Quality Control Board.

Fletemeyer, J.R. Undated. Sea Turtle Conservation Project, Broward County, Florida, 1986 report. Broward County Erosion Prevention District, Environmental Quality Control Board, Fort Lauderdale, Florida.

Fletemeyer, J.R. 1990. Kemp's ridley sea turtle nests in Palm Beach. Florida Naturalist 63(1):5.

Fletemeyer, J.R. 1991. The nesting imperative: a study of conflicts between humans and sea turtles on Southeast Florida beaches. Ed.D. dissertation. FIU, Miami, Florida.

Florida Coastal Management Program. 1995. Broward County Coastal Revegetation Plan. Coastal Currents 3(4):6.

Florida Department of Environmental Protection. 1992. Air monitoring report 1992. Division of Air Resources Management, FDEP, Tallahassee, Florida.

Florida Department of Environmental Protection. 1993. Bill Baggs Cape Florida State Recreation Area Hurricane Recovery and Restoration Plan. As approved by Governor and Cabinet July 21, 1993. Division of Recreation and Parks, FDEP, Tallahassee, Florida.

Florida Department of Environmental Protection. 1995. Conservation and Recreation Lands 1995 annual report. Office of Environmental Services, FDEP, Tallahassee, Florida.

Florida Department of Transportation. 1990. State Road No. 924 (Gratigny Parkway) landscaping plans. FDOT, District 6, Miami, Florida.

Florida Exotic Pest Plant Council. 1995. Exotic Pest Plant Council's 1995 list of Florida's most invasive species. FLEPPC, West Palm Beach, Florida.

Florida Game and Fresh Water Fish Commission. Undated(a). Did you know? There is a wildlife treasure in the heart of Miami. Pamphlet. FGFWFC, Everglades Region, West Palm Beach, Florida.

Florida Game and Fresh Water Fish Commission. 1993. Nongame Wildlife Program contracted projects that have been funded by Florida Game and Fresh Water Fish Commission as of September 15, 1993. Table. FGFWFC, Tallahassee, Florida.

Florida Game and Fresh Water Fish Commission. 1994. Nongame Wildlife Program Annual Report 1993-1994. The Skimmer 10(4).

Florida Greenways Commission. 1994. Creating a statewide greenways system: for people...for wildlife...for Florida. Report to the Governor. Florida Greenways Commission. Tallahassee, Florida.

Florida Native Plant Society. 1994. Landscape award winners. The Palmetto 1994 (Summer):14-15. The Florida Native Plant Society, Orlando, Florida.

Flynn, L. 1994. Post-hurricane natural areas management: tropical hardwood hammocks. The Palmetto 1994 (Summer):16. The Florida Native Plant Society, Orlando, Florida.

Focus, D.S., and F.J. Mazzotti. 1995. Applications of graphical models for wetland conservation. Florida Scientist 58(Suppl.1):35 (abstract).

Fourqurean, J.W. 1995. An analysis of Metropolitan Dade County, Department of Environmental Resources Management's seagrass monitoring program, fall 1985 - spring 1995. Draft final report to NMFS.

Frank, J.H. 1994a. An arrival of non-indigenous insects into Florida. Pages 53-56 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Frank, J.H. 1994b. An assessment of invasive non-indigenous insects in Florida's public lands. Pages 44-51 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Frank, J.H. 1994c. Inoculative biological control of mole crickets. Pages 467-475 *in* A. Leslie, editor. Handbook of Integrated Pest Management for Turf and Ornamentals. CRC Press, Boca Raton, Florida.

Frazel, D. 1994. Letter to J. Browder. March 22, 1994. Broward County DNRP, Water Resources Division, Fort Lauderdale, Florida.

Gaby, R., M.P. McMahon, F.J. Mazzotti, W.N. Gillies, and J.R. Wilcox. 1985. Ecology of a population of *Crocodylus acutus* at a power plant site in Florida. Journal of Herpetology 19:189-198.

Gann-Matzen, G. 1994. Restoring the wild: restoration and management of natural community fragments. Garden News 49(2):17-18. Fairchild Tropical Garden, Miami, Florida.

Garlock, M. 1994. Crocodile comeback at Turkey Point. Florida Naturalist 67(1):13-15.

Garvue, D. 1994. The Garden's endangered species program. Garden News 49(2):13-14. Fairchild Tropical Garden, Miami, Florida.

Gassman, N.J., L.B. Nye, and M.C. Schmale. 1994. Distribution of abnormal biota and sediment contaminants in Biscayne Bay, Florida. Bulletin of Marine Science 54(3):929-943.

Germain, G.J. 1994. Surface Wateter Quality Monitoring Network, South Florida Water Management District. Technical Memorandum DRE 317. SFWMD, West Palm Beach, Florida.

Gerould, S., and I.H. Kantrowitz. 1995. South Florida Ecosystem Program of the U.S. Geological Survey. Fact Sheet FS-134-95. USGS, Reston, Virginia, and Tallahassee, Florida.

Giddings, J.B. 1995. Projected impacts of a proposed development on the Florida Everglades Restoration project. Florida Scientist 58(Suppl.1):23 (Abstract).

Gleason, P.J. 1984. Introduction. Pages viii-xxv *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Gleason, P. J., and W. Spackman Jr. 1974. Calcareous periphyton and water chemistry in the Everglades. Pages 1468-1481 *in* P. J. Gleason, editor. Environments of South Florida: Present and Past II. Miami Geological Society, Coral Gables, Florida.

Glynn, P.W., A.M. Szmant, E.F. Corcoran, and S.V. Cofer-Shabica. 1989. Condition of coral reef cnidarians from the northern Florida reef tract: pesticides, heavy metals, and histopathological examination. Marine Pollution Bulletin 20:568-576.

Goldberg, W.M. 1973. The ecology of the coral-octocoral communities off the southeast Florida coast: geomorphology, species composition, and zonation. Bulletin of Marine Science 23(3):465-488.

Goodwin, J. Undated. Crandon Park, Dog Island/Rookery Island, potential land use plan prepared for the Metropolitan Dade County Park & Recreation Department. TAS, Miami, Florida.

Goodwin, J. 1994. The tern project. Tropical Audubon Bulletin, May 1994:1-2.

Gregg, J.R. 1984. Evaluation of the water management system at a single family residential site, hydrology and hydraulics of Timbercreek subdivision in Boca Raton, Florida. Technical Publication 84-11, Volume I. SFWMD, West Palm Beach, Florida.

Gregg, M.E. 1994. Invasive non-indigenous plant species impacting Florida's local-level governments and selected county-owned lands. Pages 281-298 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Grossenbacher, C. 1993. Dade County to recreate wetlands at Crandon Park. News release, August 24, 1993. Coastal Resources Section, DERM, Miami, Florida.

Gulf Engineers & Consultants, Inc. 1993. Alternatives for the dredging and disposal of sediment from the Miami Harbor (Miami River) project, Florida. Final report. Contract No. DACW17-91-D-0010. COE, Jacksonville District, Jacksonville, Florida.

Gulick, L.K. 1995. Design of a buffer along the eastern edge of the Everglades using a Geographic Information System. Florida Scientist 58(Suppl.1):35 (Abstract).

Haddad, K., P. Matthews, T. Culliton, D. Lott, and J. Thomas. 1995. Interagency Spatial Information Workshop on the South Florida Ecosystem. Volume II: Information Surveys. West Palm Beach, Florida, September 22-23, 1994. FGDC, FDEP, NBS, NOAA, SFERTF, and SFWMD.

Haire, W.J., and C. Lietz. 1993. Water resources data - Florida, 1992. Volume 2B: South Florida ground water. Water-Data Report FL-92-2B. USGS, Miami, Florida.

Haire, W.J., and C. Price. 1993. Water resources data - Florida, 1992. Volume 2A: South Florida surface water. Water-Data Report FL-92-2A. USGS, Miami, Florida.

Hale, K.K. 1993. Biscayne Bay: a bibliography of the marine environment. Technical Paper 67. Florida Sea Grant College Program, Gainesville, Florida.

Hall, J.R. 1995. Letter to B.J. Bernier, District Environmental Administrator, Florida Department of Transportation, from Chief, Regulatory Division, Jacksonville District Corps of Engineers. January 24, 1995. COE, Jacksonville District, Jacksonville, Florida.

Hamrick, J.L. 1995. Genetic diversity within and among populations of South Florida slash pine, *Pinus elliottii* var. *densa*. Final report. Appendix 4 *in* J. Maguire, principal author. Restoration Plan for Dade County's pine rockland forests following Hurricane Andrew. DERM, Miami, Florida.

Hancock, D., and D. Keating. 1995. Dade population tops two million. August 9, 1995. The Miami Herald, Miami, Florida. p. 1B.

Hardee, J., R.A. Miller, and H.C. Mattraw Jr. 1979. Stormwater-runoff data from a multifamily residential area, Dade County, Florida. Open-File Report 79-1295. USGS, Tallahassee, Florida.

Harper, R.M. 1927. Natural resources of southern Florida. 18th Annual Report of the Florida Sate Geological Survey:27-206. Tallahassee, Florida.

Harrell, J.B., editor. Undated. Replanting the urban forest after Hurricane Andrew, a South Florida tree selection guide. FDACS, Tallahassee, Florida.

Harris, B.A., W.J. Conley, and J.A. Huff. 1984. The status of Florida's nesting sea turtle populations from 1979 through 1983. FDNR, St. Petersburg, Florida.

Harshbarger, J.C., P.M. Spero, and N.M. Wolcott. 1993. Neoplasms in wild fish from the marine ecosystem emphasizing environmental interactions. Pages 157-176 *in* J.A. Couch and J.W. Fournie, editors. Pathobiology of Marine and Estuarine Organisms. CRC Press, Boca Raton, Florida.

Hela, I., C.A. Carpenter Jr., and J.K. McNulty. 1957. Hydrography of a positive, shallow, tidal bar-built estuary (report on the hydrography of the polluted area of Biscayne Bay). Bulletin of Marine Science of the Gulf and Caribbean 7(1):47-99.

Herr, J.W., and J.E. Shaw. 1989. South Florida Water Management District ambient ground water quality. Technical Publication 89-1. Water Quality Division, Resource Planning Department, C&SF FCD, West Palm Beach, Florida.

Hibler, J. 1995. Temperature dependent emergence and social behavior in loggerhead sea turtle (*Caretta caretta*) hatchlings. Florida Scientist 58(Suppl.1):30 (abstract).

Hildebrand, E.L. 1977. Mangrove sediments in South Florida: soluble organic carbon and the growth physiology of an epipelic diatom. Master's thesis. UM, Coral Gables, Florida.

Hoffman, W., editor. 1994. Report of the Everglades Restoration Success Workshop. NAS, Tavernier, Florida.

Hoffmeister, J.E., and H.G. Multer. 1965. Fossil mangrove reef of Key Biscayne, Florida. Geological Society of America Bulletin 76:845-852.

Hogg, R.G. 1976. Established exotic cichlid fishes in Dade County, Florida. Florida Scientist 39:97-103.

Holler, J.D. 1989. Water quality efficiency of an urban commercial wet detention stormwater management system at the Boynton Beach Mall in south Palm Beach County, Florida. Florida Scientist 52:48-57.

Horvitz, C.C. 1994. Hammocks and hurricanes: non-indigenous plants threaten tropical hardwood hammocks after Hurricane Andrew. Pages 169-170 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Howie, B., and B.G. Waller. 1986. Chemical effects of highway runoff on the surficial aquifer, Broward County, Florida. Water-Resources Investigations Report 86-4200. USGS, Tallahassee, Florida.

Huck, R.B. 1993. Restoration initiative for Cape Florida State Recreation Area following Hurricane Andrew. Draft. FDEP, Division of Recreation and Parks, Tallahassee.

Huck, R.B. 1995. A centennial review: the historic natural landscape of Key Biscayne, Dade County, Florida. Florida Scientist 58:335-351.

Humphrey, S.R., Kern, W.H. Jr., and M.S. Ludlow. 1987. Status survey of seven Florida mammals. Final report. Technical Report No. 25. Florida Cooperative Fish & Wildlife Research Unit, Gainesville, Florida.

Humphreys, J. 1993. Nationwide study looks at pesticide threat to estuaries. Fathom 5(2):3-4.

Hyler, W.R. 1995. Vervet monkeys in the mangrove ecosystem of southeastern Florida: preliminary census and ecological data. Florida Scientist 58:38-43.

Ignacio, C. 1994. Letter with tables to C. Goodyear, February 22, 1994. DERM, Environmental Monitoring Division, Miami, Florida.

Irwin, G.A. Undated. National water summary 1990-91 -- Florida stream water quality. Water-Supply Paper 2400. USGS, Tallahassee.

Jackson, J., and T. Strowd. 1995. Enhancing the Everglades and urban environment: East Coast Buffer. Everglades Connection IV(1):1-3. SFWMD, West Palm Beach, Florida.

James, F.C. 1994. An assessment of non-indigenous birds in Florida's public lands. Pages 96-103 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Jettmar, R.U., G.K. Young, A.I. Perez, and R. Oros. 1980. Dynamic water quality modeling in southeast Florida. Proceedings of the American Society of Civil Engineers, Journal of the Environmental Engineering Division 106 (EE1):105-124.

Johnson, A.F., and M.G. Barbour. 1990. Dunes and maritime forests. Pages 429-480 (Chapter 13) *in* R.L. Meyers and J.J. Ewel, editors. Ecosystems of Florida. University of Central Florida Press, Orlando, Florida.

Johnson, A.F. and J.W. Muller. 1993. An Assessment of Florida's Remaining Coastal Upland Natural Communities: Final Summary Report. FNAI, Tallahassee, Florida.

Johnson, A.F., J.W. Muller, and K.A. Bettinger. 1993. An Assessment of Florida's Remaining Coastal Upland Natural Communities: Southeast Florida. FNAI, Tallahassee, Florida.

Johnson Controls World Services. 1995. Annual survey locations - from EMAP-E summer surveys to measure indicators of the health of plants and animals, the quality of their surroundings, and the presence of pollutants. Report 95-05-51. National Biological Survey Operations, Johnson Controls World Services, Gulf Breeze, Florida.

Joint Center for Environmental and Urban Problems. 1985a. C-51 Basin Growth Management Conference. Background paper. FAU, Boca Raton, and FIU, North Miami, Florida.

Joint Center for Environmental and Urban Problems. 1985b. South Florida's wastewater reuse systems. Phase one of a three phase project. FAU, Boca Raton, and FIU, North Miami, Florida.

Joint Center for Environmental and Urban Problems. 1985c. South Florida's wastewater reuse systems. Phase two of a three phase project. FAU, Boca Raton, and FIU, North Miami, Florida.

Joint Center for Environmental and Urban Problems. 1985d. South Florida's wastewater reuse systems. Final report. FAU, Boca Raton, and FIU, North Miami, Florida.

Joint Center for Environmental and Urban Problems. 1993. Biennial Report 1991-1993. FAU, Boca Raton, and FIU, North Miami, Florida.

Joint Center for Environmental and Urban Problems and Florida Atlantic University Institute of Government. 1988a. Directions 88: charting the course of Palm Beach County. Background paper. FAU, Boca Raton, and FIU, North Miami, Florida.

Joint Center for Environmental and Urban Problems and Florida Atlantic University Institute of Government. 1988b. Directions 88: charting the course for Palm Beach County. Policy statement on the management of growth for Palm Beach County. FAU, Boca Raton, and FIU, North Miami, Florida.

Kale, H.W. II. 1978. Birds. Volume 2, Rare and Endangered Biota of Florida (P.C.H. Pritchard, series editor). University Presses of Florida, Gainesville, Florida.

Kenworthy, W.J., and A.C. Schwarzschild. 1994a. First quarterly report for contract no. C-5134. Submitted to SFWMD, West Palm Beach, Florida.

Kenworthy, W.J., and A.C. Schwarzschild. 1994b. Second quarterly report for contract no. C-5134. Submitted to SFWMD, West Palm Beach, Florida.

Kenworthy, W.J., and A.C. Schwarzschild. 1995a. Preliminary evaluation of an optical water quality model for use at two locations in north Biscayne Bay, Fl. Progress report (third). Submitted to SFWMD, West Palm Beach, Florida.

Kenworthy, W.J., and A.C. Schwarzschild. 1995b. Estimation of the minimum light requirements of *Thalassia testudinum*, *Halodule wrightii* and *Syringodium filiforme* in Biscayne Bay, Fl. Progress report (fourth). Submitted to SFWMD, West Palm Beach, Florida.

Kerr, O. 1991. The demographic future of South Florida. Pages 87-96 *in* T.D. Boswell, editor. South Florida: The Winds of Change. Annual Conference, Association of American Geographers, Miami, Florida.

Khanal, N.N. 1975. Hydrologic aspects of on-site retention systems for urban storm runoff. Technical Publication 75-4. Resource Planning Department, C&SF FCD, West Palm Beach, Florida.

Khanal, N. 1982. Performance of district structures during critical storm events in West Miami, and proposed alternatives to reduce flooding. Technical Publication 82-7. Resource Planning Department, C&SF FCD, West Palm Beach, Florida.

Khanal, N. 1987. Desalination, a viable alternative for local government water supply planning in South Florida. Technical Publication 87-4. SFWMD, West Palm Beach, Florida.

Kimball, M.C., and H.J. Teas. 1975. Nitrogen fixation in mangrove areas of southern Florida. Pages 654-660 *in* G.E. Walsh, S.C. Snedaker, and H.J. Teas, editors. Proceedings of the International Symposium on Biology and Management of Mangroves. Volume II. IFAS, UF, Gainesville, Florida.

King, W, and T. Krakauer. 1966. The exotic herpetofauna of Southeast Florida. Quarterly Journal of the Florida Academy of Sciences 29(2):144-154.

Kirchhoff, M. 1995. Florida Bay partnerships: positive steps toward restoring the Bay. Everglades Connection IV(2):1-3. SFWMD, West Palm Beach, Florida.

Klein, H., J.T. Armbruster, B.F. McPherson, and H.J. Freiberger. 1975. Water and the South Florida environment. Water-Resources Investigation 24-75. USGS, Tallahassee, Florida.

Klein, H., J.E. Hull. 1978. Biscayne Aquifer, Southeast Florida. Water-Resources Investigation 78-107. USGS, Miami, Florida.

Klein, J. Undated. South Dade rockland hammocks. Fact sheet. DERM, Miami, Florida.

Kohout, F.A, and J.H. Hartwell. 1967. Hydrologic effects of Area B flood control plan on urbanization of Dade County, Florida. Report of Investigations No. 47. Florida Geological Survey, Tallahassee, Florida.

Kohout, F.A., and M.C. Kolipinski. 1967. Biological zonation related to groundwater discharge along the shore of Biscayne Bay, Miami, Florida. Pages 488-499 *in* G.A. Lauff, editor. Estuaries. Publication No. 83. American Association for the Advancement of Science, Washington, D.C.

Kollin, J. 1994. Unkillable shrub soon to be planted roadside. Tropical Trails 1994(Spring):4-5, as reprinted from the Sun Sentinel.

Kreitman, A., and L.A. Wedderburn. 1984. Hydrogeology of South Florida. Pages 405-426 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Kushlan, J.A. 1988. Conservation and management of the American crocodile. Environmental Management 12:777-790.

Kushlan, J.A., and T.E. Lodge. 1974. Ecological and distributional notes on the freshwater fish of southern Florida. Florida Scientist 37:110-128.

Kushlan, J.A., and F.J. Mazzotti. 1989. Historic and present distribution of the American crocodile in Florida. Journal of Herpetology 23(1):1-7.

Kushlan, J.A., and D.A. White. 1977. Nesting wading bird populations in southern Florida. Florida Scientist 40:65-72.

Land Trust of Dade County, Trust for Public Land, and Metropolitan Dade County Park and Recreation Department. 1994. Greenways for Dade: an integrated system of linear corridors linking people and places. Land Trust of Dade County, Coconut Grove, Florida.

Laroche, F.B., and A.P. Ferriter. 1992. The rate of expansion of melaleuca in South Florida. Journal of Aquatic Plant Management 30:62-65.

Larsen and Associates. 1992. South Florida Limestone Mining Coalition Year 2050 Freshwater Lake Belt Plan. Larsen and Associates, Miami, Florida.

Layne, J.N. 1978. Mammals. Volume 1, Rare and Endangered Biota of Florida (P.C.H. Pritchard, series editor). University Presses of Florida, Gainesville, Florida.

Layne, J.N. 1994. Non-indigenous mammals in Florida. Pages 79-95 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Leach, S.D., H. Klein, and E.R. Hampton. 1972. Hydrologic effects of water control and management of southeastern Florida. Report of Investigation No. 60. USGS, Tallahassee, Florida.

Leahy, P.P., and W.G. Wilber. 1991. National Water-Quality Assessment Program. Water fact sheet. Open-file report 91-54. USGS, Reston, Virginia.

Lee, T.N. 1976. Circulation and exchange processes in southeast Florida's coastal lagoons. Pages 51-63 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Leone-Kabler, S., S.L. Shaw, P. Lutz. 1994. Effects of Hurricane Andrew on sea turtle nesting beaches of South Florida. Page 247 *in* B.A. Schroeder and B.E. Witherington, editors. Proceedings of the Thirteenth Annual Symposium on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-341. NMFS, Miami, Florida.

Lin, S., J. Lane, and J. Marban. 1984. Meteorological and hydrological analysis of the 1980-1982 drought. Technical Publication 84-7. SFWMD, West Palm Beach, Florida.

Link, E.J., and C. Lippincott. Undated. The Doc Thomas house and grounds, an approach to xeriscape. Brochure. TAS/The Junior League of Miami, Inc., Miami, Florida.

Loope, L.L., D.W. Black, S. Black, and G.N. Avery. 1979. Distribution and abundance of flora in limestone rockland pine forests of southeastern Florida. Report T-547. SFRC, ENP, Homestead, Florida.

Lovestrand, E. 1990. Living treasures of the Florida scrub. Wild Florida, Volume 1: Florida's unique natural areas, scrub habitat. Pamphlet. Nongame Wildlife Program, FGFWFC, Tallahassee, Florida.

Lynch, M.P., B.L. Laird, N.B. Theberge, and J.C. Jones. 1976. An assessment of estuarine and nearshore marine environments. OBS/FWS-76/05. FWS, Washington, D.C.

MacAdam, G. 1990. Environmental protection through citizen action. Parks and Recreation 25(October):46-51.

MacVicar, T.K., T. VanLent, and A. Castro. 1984. South Florida Water Management Model documentation report. Technical Publication 84-3. SFWMD, West Palm Beach, Florida.

Makemson, J., K. Mayo, and J. Sonnenberg. 1992. Bear Cut Preserve in Crandon Park, environmental restoration and management study. Metro Dade PRD, Miami, Florida.

Maguire, J. 1995. Restoration Plan for Dade County's pine rockland forests following Hurricane Andrew. DERM, Miami, Florida.

Mann, T.M. 1977. Impact of developed coastline on nesting and hatchling sea turtles in southeastern Florida. Master's thesis. FAU, Boca Raton, Florida.

Marella, R.L. 1992. Water withdrawals, use, and trends in Florida, 1990. Water-Resources Investigations Report 92-4140. USGS, Tallahassee, Florida.

Margolis, W.E. 1993. Nesting periodicity of *Caretta caretta* in Broward County, Florida. Master's thesis. Nova University Oceanographic Center, Fort Lauderdale, Florida.

Mattison, C., C.M. Burney, and L. Fisher. 1990. Sea turtle nesting and hatching success in Broward County, Florida, 1989. Pages 165-168 *in* T.H. Richardson, J.I. Richardson, M. Donnelly, editors. Proceedings of

the Tenth Annual Workshop on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFC-278. NMFS, Miami, Florida.

Mattison, C., C.M. Burney, and L. Fisher. 1994. Trends in the spatial distribution of sea turtle activity on an urban beach (1981-1992). Pages 102-104 *in* B.A. Schroeder and B.E. Witherington, editors. Proceedings of the Thirteenth Annual Symposium on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-341. NMFS, Miami, Florida.

Mattraw, H.C., J. Hardee, and R.A. Miller. 1978a. Urban stormwater data for a residential area, Pompano Beach, Florida. Open-File Report 78-324. USGS, Tallahassee, Florida.

Mattraw, H.C., J.E. Hull, and H. Klein. 1978b. Ground-water quality near the Northwest 58th Street solid-waste disposal facility, Dade County, Florida. Water-Resources Investigations Report 78-45. USGS, Tallahassee, Florida.

Mattraw, H.C., and R.A. Miller. 1981. Stormwater quality processes for three land-use areas in Broward County, Florida. Water-Resources Investigations Report 81-23. USGS, Tallahassee, Florida.

Mattraw, H.C., and C.B. Sherwood. 1977. Quality of stormwater runoff from a residential area, Broward County, Florida. Journal of Research USGS 5(6):823-834.

McCann, J.A., L.N. Arkin, and J.D. Williams. 1995. Nonindigenous aquatic and selected terrestrial species of Florida: status, pathway, and time of introduction, present distribution, and significant ecological and economic effects. Draft report. NBS, National Fisheries Research Center, Gainesville, Florida.

McCluney, J., and R. McCluney. 1969. A new concept of the value of land. Pages 85-91 *in* W.R. McCluney, editor. The Environmental Destruction of South Florida. University of Miami Press, Coral Gables, Florida.

McCoy, H.J., and J. Hardee. 1970. Ground-water resources of the lower Hillsboro Canal area, southeastern Florida. Report of Investigation No. 55. USGS, Tallahassee, Florida.

McDiarmid, R.W. 1978. Amphibians & reptiles. Volume 3, Rare and Endangered Biota of Florida (P.C.H. Pritchard, series editor). University Presses of Florida, Gainesville, Florida.

McHargue, L., and R. Hammer. 1994. Metro Parks' natural areas management. Garden News 49(2):15-16. Fairchild Tropical Garden, Miami, Florida.

McKenzie, D. 1994. Letter to R. DeHan, Florida Department of Environmental Protection, plus enclosures summarizing results of reconnaissance of agrichemicals in water from open irrigation wells in Dade County, Florida. April 18, 1994. USGS, Tallahassee, Florida.

McPherson, B.F. 1994. National Water-Quality Assessment Program -southern Florida. Water fact sheet. Open-file report 94-57. USGS, Tallahassee, Florida.

McPherson, B.F., G.Y. Hendrix, H. Klein, and H.M. Tyus. 1976. The environment of South Florida, a summary report. Geological Survey Professional Paper 1011. GPO, Washington, D.C.

Metcalf & Eddy. 1992. Treatability study for the City of Hollywood Phase 1 - office studies. Draft report.

Metcalf & Eddy and Berry & Calvin. 1992. Preliminary design report, City of Hollywood water treatment plant upgrade. Submitted to City of Hollywood, Florida.

Metro-Dade County Planning Department. 1988a. Coastal management element support component. Metro-Dade County Comprehensive Development Master Plan for 2000 and 2010, effective December 1988. Metro-Dade County Planning Department, Miami, Florida.

Metro-Dade County Planning Department. 1988b. Support components of the Port of Miami River subelement. Metro-Dade County Comprehensive Development Master Plan for 2000 and 2010, effective December 1988. Metro-Dade County Planning Department, Miami, Florida.

Metro-Dade County Planning Department. 1989. Conservation, aquifer recharge and drainage element support component. Metro-Dade County Comprehensive Development Master Plan for 2000 and 2010, effective December 1988. Metro-Dade County Planning Department, Miami, Florida.

Metropolitan Dade County Planning Department. 1970. South Bay area study. Metropolitan Dade County Planning Department, Miami, Florida.

Metropolitan Dade County Planning Department. 1993. Adopted components, Comprehensive Development Master Plan for Metropolitan Dade County, Florida. Metropolitan Dade County Planning Department, Miami, Florida.

Miami Herald. 1994. Report: water quality too low for one in five. July 28, 1994. The Miami Herald, Miami, Florida.

Miami Herald. 1995a. Repairs done on sewage pipe. September 3, 1995. The Miami Herald, Miami, Florida.

Miami Herald. 1995b. Waters still unsafe for swimming. August 19, 1995. The Miami Herald, Miami, Florida.

Michel, J.F. 1976. The impact of works of man on the physical regime of Biscayne Bay. Pages 265-270 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Mierau, R. 1975. Water availability in the Dade County agricultural areas. Memorandum Report DRE-50. SFWMD, West Palm Beach, Florida.

Miller, P.C. 1972. Bioclimate, leaf temperature, and primary production in red mangrove canopies in South Florida. Ecology 53(1):22-45.

Miller, P.C. 1975. Simulation of water relations and net photosynthesis in mangroves in southern Florida. Pages 615-631 *in* G.E. Walsh, S.C. Snedaker, and H.J. Teas, editors. Proceedings of the International Symposium on Biology and Management of Mangroves. Volume II. IFAS, UF, Gainesville, Florida.

Miller, R.A., and H.C. Mattraw Jr. 1982. Storm water runoff quality from three land-use areas in South Florida. Water Resources Bulletin 18(3):513-519.

Millsap, B.A., J.A. Gore, D.E. Runde, and S.I. Cerulean. 1990. Setting priorities for the conservation of fish and wildlife species in Florida. Wildlife Monographs 111:1-57.

Millsap, P. Undated. Florida's burrowing owl *Athene cunicularia floridana*. Pamphlet. Nongame Wildlife Program, FGFWFC, Tallahassee, Florida.

Milton, S.L., S. Leone-Kabler, A.A. Schulman, and P.L. Lutz. 1994. Effects of Hurricane Andrew on the sea turtle nesting beaches of South Florida. Bulletin of Marine Science 54(3):974-981.

Moler, P.E., C.L. Abercrombie III, and D.K. Jansen. 1992. Aspects of the population biology of the American crocodile. Final performance report, 1 July 1991 - 30 June 1992. Florida Statewide Wildlife Research Study No. 7534. FGFWFC, Gainesville, Florida.

Montague, J.R., A. Morales, and I. Gonzalez. 1995. Population density of sea urchins (*Lytechnius variegatus*) in relation to standing crop of seagrasses in Biscayne Bay. Florida Scientist 58(Suppl.1):13 (Abstract).

Montgomery, L. 1975. Glades conservation - at a snail's pace. December 14, 1975. The Miami Herald, Miami, Florida.

Moran, M.B. 1979. Coastal zone management in Pompano Beach; implementation in an urban coastal city. Master's Thesis. FAU, Boca Raton, Florida.

Morin, O.J. 1987. Pages 9-33 *in* O.K. Buros, editor. Desalination in South Florida. National Water Supply Improvement Association and SFWMD.

Muhs, A. 1994. Tiny, rare wildflower wins right to bloom. March 23, 1994. The Miami Herald, Miami, Florida.

Muller, J.W., E.D. Hardin, D.R. Jackson, S.E. Gatewood, and N. Caire. 1989. Summary report on the vascular plants, animals and plant communities endemic to Florida. Nongame Wildlife Program Technical Report No. 7. FGFWFC, Tallahassee, Florida.

Muller, P.O. 1991. The urban geography of South Florida. Pages 62-69 *in* T.D. Boswell, editor. South Florida: The Winds of Change. Annual Conference, Association of American Geographers, Miami, Florida.

National Audubon Society. 1994. Report on water supply preserves. NAS, Everglades Restoration Campaign, Miami, Florida.

National Marine Fisheries Service and U.S. Fish and Wildlife Service. 1991a. Recovery Plan for U.S. population of loggerhead turtle. NMFS, Washington, D.C.

National Marine Fisheries Service and U.S. Fish and Wildlife Service. 1991b. Recovery Plan for U.S. population of Atlantic green turtle. NMFS, Washington, D.C.

National Marine Fisheries Service and U.S. Fish and Wildlife Service. 1992. Recovery Plan for leatherback turtles in the U.S. Caribbean, Atlantic and Gulf of Mexico. NMFS, Washington, D.C.

National Marine Fisheries Service and U.S. Fish and Wildlife Service. 1994. Draft Recovery Plan for hawksbill turtles in the U.S. Caribbean, Atlantic and Gulf of Mexico. NMFS, Washington, D.C.

Nesbitt, S.A., J.C. Ogden, H.W. Kale II, B.W. Patty, and L.A. Rowse. 1982. Florida atlas of breeding sites for herons and their allies: 1976-78. FWS/OBS-81/49. FWS, Washington, D.C.

Neuharth, J. 1995. East Coast Buffer purchase is first to use P-2000 funds. News release, October 12, 1995. SFWMD, West Palm Beach, Florida.

Nicholas, J.C. 1974. Land utilization in South Florida: a description of the historical development of urban and agricultural land use patterns. PB-231 942. South Florida Environmental Project: Ecological Report No. DI-SFEP-74-47. DOI, Washington, D.C.

Northwest Dade County Freshwater Lake Plan Implementation Committee. 1995. 1995 progress report. December 31, 1995. SFWMD, West Palm Beach, Florida.

Nova Southeastern University. 1995. Lake and littoral studies, Dade County Lake Belt Plan. First annual report submitted to Metro-Dade County Clerk of the Board of Commissioners, April 1995. Oceanographic Center, Nova Southeastern University, Dania, Florida.

Obeysekera, J., R.L. Barkau, and C. de Rojas. 1993. Linking hydrologic and hydraulic routing models in low relief basins of South Florida. DOR Paper 121. SFWMD, West Palm Beach, Florida.

O'Brien, J.J. 1994. Research on South Florida *Galactia (Fabaceae)*. Plant Conservation 8(1):1-3.

Odum, W..E., C.C. McIvor, and T.J. Smith III. 1982. The ecology of the mangroves of South Florida: a community profile. FWS/OBS-81/24. FWS, Washington, D.C.

Office of Technology Assessment. 1993. Harmful Non-Indigenous Species in the United States. OTA-F-565. GPO, Washington, D.C.

Ogden, J.C. 1978. Status and nesting of the American crocodile, *Crocodylus acutus*, (Reptilis, Crocodilidae) in Florida. Journal of Herpetology 12(2):183-196.

1000 Friends of Florida. 1995a. Local projects show diversity. Florida Greenways 3(1). FOF, Tallahassee, Florida.

1000 Friends of Florida. 1995b. Citizens seek a new future for western Dade, Broward. Foresight 8(1):4. FOF, Tallahassee, Florida.

1000 Friends of Florida. 1995c. Planning South Florida's last frontier. Florida Network for Successful Communities Newsletter 2(1):1-4. FOF, Tallahassee, Florida.

1000 Friends of Florida. 1995d. Planning one of Florida's last frontiers: a roundtable vision for the future of the western C-9 basin. Workshop report. FOF, Tallahassee, Florida.

1000 Friends of Florida/The Conservation Fund. Undated. Broward County Greenways Network project synopsis. Florida Greenways Project. FOF/The Conservation Fund, Tallahassee, Florida.

1000 Friends of Florida/The Conservation Fund. 1994. Greenways for Dade. Florida Greenways 2(2):4. FOF/The Conservation Fund, Tallahassee, Florida.

Orians, G.H., M. Bean, R. Lande, K. Loftin, S. Pimm, R.E. Turner, and M. Weller. 1992. Report of the Advisory Panel on the Everglades and Endangered Species. Audubon Conservation Report No. 8. NAS, New York.

Osborn, R.G., and T.W. Custer. 1978. Herons and their allies: atlas of Atlantic Coast colonies, 1975 and 1976. FWS/OBS-77/08. FWS, Washington, D.C.

Owre, O.T. 1976. The avifauna of Biscayne Bay. Pages 213-226 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Paddon, J., and D. Suman. 1995. The Virginia Key campground. Pages 155-175 *in* D. Suman, M. Shivlani, and M. Villanueva, editors. Urban Growth and Sustainable Habitats: Case Studies of Policy Conflicts in South Florida's Coastal Environment. Division of Marine Affairs and Policy, RSMAS, Miami, Florida.

Padgett, D.G.J. 1987. One foot drawdown zones of influence surrounding municipal water supply wellfields in Palm Beach County. Technical Memorandum DRE-238. SFWMD, West Palm Beach, Florida.

Pait, A.S., A.E. De Souza, and D.R.G. Farrow. 1992. Agricultural Pesticide Use in Coastal Areas: A National Summary. Strategic Environmental Assessments Division, National Ocean Service, NOAA, Rockville, Maryland.

Palm Beach County Department of Environmental Resources Management. Undated. Fact sheets on ESL sites. Palm Beach County DERM, West Palm Beach, Florida.

Palm Beach County Department of Environmental Resources Management. 1991. Palm Beach County Environmentally Sensitive Lands Referendum, March 12, 1991. Information sheet, list, and map. Palm Beach County DERM, West Palm Beach, Florida.

Parker, G. 1951. Geologic and hydrologic factors in the perennial yield of the Biscayne aquifer. American Water Works Association Journal 43:817-834.

Parker, G. 1984. Hydrology of the pre-drainage system of the Everglades in southern Florida. Pages 28-37 *in* P.J. Gleason, editor. Environments of South Florida, Present and Past II. Miami Geological Society, Coral Gables, Florida.

Parker, G.G., G.E. Ferguson, S.K. Love. 1955. Water resources of southeastern Florida with special reference to the geology and ground water of the Miami area. Geological Survey Water-Supply Paper 1255. GPO, Washington, D.C.

Parker, J. 1983. Landscaping: a key to energy conservation in Florida. Florida Nurseryman 30:12.

Pfeuffer, R.J. 1985. Pesticide residue monitoring in sediment and surface water bodies within the South Florida Water Management District. Technical Publication 85-2. Water Chemistry Division, Resource Planning Department, C&SF Water Management District, West Palm Beach, Florida.

Phillips, W.S. 1940. A tropical hammock on the Miami (Florida) limestone. Ecology 21:166-175.

Pitt, W.A.J. Jr. 1974. Effects of septic tank effluent on ground-water quality, Dade County, Florida: an interim report. Open file report 74010. USGS, Tallahassee, Florida, in cooperation with Dade County, Florida.

Pitt, W.A.J. Jr., H.C. Mattraw Jr., and H. Klein. 1975. Ground-water quality in selected areas serviced by septic tanks, Dade County, Florida. Open File Report 75-607. USGS, Tallahassee, Florida.

Pool, D.J., A.E. Lugo,and S.C. Snedaker. 1975. Litter production in mangrove forests of southern Florida and Puerto Rico. Pages 213-237 *in* G.E. Walsh, S.C. Snedaker, and H.J. Teas, editors. Proceedings of the International Symposium on Biology and Management of Mangroves. Volume I. IFAS, UF, Gainesville, Florida.

Pope, R.L., and P.B. Schroeder. 1979. A limnological survey of Dade County lakes. Abstract. Florida Scientist 42(Suppl.):32.

Post, Buckley, Schuh, & Jernigan, Inc. 1992. Wastewater reuse feasibility study. Volumes I and II (Appendices). Prepared for Miami-Dade Water and Sewer Authority Department, Metropolitan Dade County, Florida.

Pritchard, P.C.H. 1979. Encyclopedia of turtles. T.F.H. Publications, Inc., Neptune, New Jersey.

Puckett, C., and R. Franz. 1991. The gopher tortoise: a species in decline. Pamphlet. Gopher Tortoise Council, Gainesville, Florida.

Quinn, T.G. 1994. Non-indigenous animal regulatory program. Pages 272-280 *in* An assessment of invasive non-indigenous species in Florida's public lands. FDEP, Tallahassee, Florida.

Reark, J.B. 1975. A history of the colonization of mangroves on a tract of land on Biscayne Bay, Florida. Pages 776-804 *in* G.E. Walsh, S.C. Snedaker, and H.J. Teas, editors. Proceedings of the International Symposium on Biology and Management of Mangroves. Volume I. IFAS, UF, Gainesville, Florida.

Reddy, K.R. 1982. Mineralization of nitrogen in organic soils. Soil Science Society of America Journal 46:561-566.

Reiners, R., M. Salmon, and C. Lavin. 1994. Hatchling misorientation on an urban beach (Boca Raton, Florida). Page 146 *in* B.A. Schroeder and B.E. Witherington, editors. Proceedings of the Thirteenth Annual Symposium on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-341. NMFS, Miami, Florida.

Restrepo, J.I., C. Bevier, and D. Butler. 1992. A three-dimensional finite difference ground water flow model of the surficial aquifer system, Broward County, Florida. Technical Publication 92-05. SFWMD, West Palm Beach, Florida.

Rich, E.R. 1969. The population explosion in Dade County. Pages 41-43 *in* W.R. McCluney, editor. The Environmental Destruction of South Florida. University of Miami Press, Coral Gables, Florida.

Richardson, D.R. 1977. Vegetation of the Atlantic Coastal Ridge of Palm Beach County, Florida. Florida Scientist 40:281-330.

Rielinger, D.M. 1991. Respiration in black mangrove (*Avicennia germinans* [L.] Stern) pneumatophores under submerged and oiled conditions. Master's Thesis. UM, Coral Gables, Florida.

Ring, R.G. 1994. Letter to S. Poitier, Chairman, Broward County Board of Commissioners, on proposed amendment PC 94-1 to the Broward County Land Use Plan. February 9, 1994. ENP, Homestead, Florida.

Robson, M. 1989a. Southeastern beach mouse survey. Final performance report. FGFWFC, Bureau of Nongame Wildlife, Tallahassee, Florida.

Robson, M. 1989b. Status survey of the Florida mastiff bat. Final performance report. FGFWFC, Bureau of Nongame Wildlife, Tallahassee, Florida.

Robson, M., F.J. Mazzotti, and T. Parrott. 1989. Recent evidence of the mastiff bat in southern Florida. Florida Field Naturalist 17:81-82.

Rodis, H.G., and L.F. Land. 1976. The shallow aquifer--a prime freshwater resource in eastern Palm Beach County, Florida. Water-Resources Investigations 76-21. USGS, Tallahassee, Florida.

Rodriguez, R. 1994. Letter with tables to Carole Goodyear dated May 17, 1994. Dade County DERM, Water Management Division, Miami, Florida.

Roessler, M.A., and G.L. Beardsley. 1974. Biscayne Bay: its environment and problems. Florida Scientist 37:186-204.

Roessler, M.A., G.L. Beardsley, and D.C. Tabb. 1977. New records of the introduced snail, *Melanoides tuberculata* (Mollusca: Thiaridae) in South Florida. Florida Scientist 40:87-94.

Ross, M.S., J. Ley, and J.F. Meeder. 1994. A historical examination of the coastal vegetation gradient in the southeastern Everglades. Abstract *in* Meeder, J.F., and R.E. Turner, organizers. The Second Coastal Wetland Ecology and Management Symposium: Sustained Wetland Productivity through Scientific Research, December 6-8, 1994, Key Largo, Florida. Program with abstracts. FIU, LSU, NBS, NMFS, and Remote Data Systems, Inc.

Russell, G.M., and A.L. Higer. 1988. Assessment of ground-water contamination near Lantana landfill, southeast Florida. Ground-Water 26:156-164.

Russell, P. 1994. As concrete spreads, flooding potential grows. July 24, 1994. The Miami Herald, Miami, Florida.

Russo, T.N. 1973. Discovery of the gastropod snail *Melanoides (Thiara) tuberculata* (Muller) in Florida. Florida Scientist 36:212-213.

Rutchey, K. 1992. The response of vegetation and benthic macroinvertebrates to constructed littoral habitat in Canal 51. Technical Memorandum DRE-306. SFWMD, West Palm Beach, Florida.

Salmon, M., M. Tolbert, M. Goff. 1994. Nesting patterns of loggerhead sea turtles on an urban beach (Boca Raton, Florida). Page 156 *in* B.A. Schroeder and B.E. Witherington, editors. Proceedings of the Thirteenth Annual Symposium on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-341. NMFS, Miami, Florida.

Scheidt, D.J. 1989. Pesticides and Everglades National Park: South Florida use and threat. Pages 365-375 *in* D.W. Fisk, editor. Wetlands: Concerns and Successes. Symposium Proceedings, September 17-22, 1989, Tampa, Florida. Technical Publication Series TPS-89-3. AWRA, Bethesda, Maryland.

Scheidt, D. 1995. Meeting summary: endosulfan in South Florida. EPA, Region IV, Atlanta, Georgia.

Scheidt, D.J., and M.D. Flora. 1983. Mowry Canal (C-103): water quality and discharge into Biscayne Bay, 1975-1981. Report SFRC-83/06. SFRC, ENP, Homestead, Florida.

Schmale, M.C. 1994. The effect of historical contaminants in biota in Biscayne Bay, Florida. Report No. 5 (final report and summary of study) and Deliverable 8 to SFWMD (Contract No. C90-1334-3. Division of Marine Biology and Fisheries, RSMAS, Miami, Florida.

Schneider, J.J. 1973. Effects on water quality in the shallow aquifer due to the operation of the Cross State Dump, Palm Beach County, Florida. Open File Report 73011. USGS, Tallahassee, Florida.

Schroeder, M.C., H. Klein, and N.D. Hoy. 1958. Biscayne Aquifer of Dade and Broward counties, Florida. Report of Investigations No. 17. USGS, Tallahassee, Florida.

Schroeder, P. 1994. Plant Restoration Plan for Cape Florida SRA. Draft. FDEP, Division of Recreation and Parks, Bill Baggs Cape Florida SRA, Key Biscayne, Florida.

Schroeder, P., and R. Pope. 1979. A cluster analysis comparison of Dade County rockpit lakes and 1969 and 1976. Abstract. Florida Scientist 42(Suppl.):33.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

Scott, G.I., M.H. Fulton, and G.T. Chandler. 1994a. A survey of sediment toxicity in Biscayne Bay, Florida. Proposal submitted to NOAA Status and Trends Program, Seattle, Washington.

Scott, G.I., M.H. Fulton, J.W. Daugomah, E.D. Strozier, P.B. Key, P.L. Pennington, B.C. Thompson, E.F. Wirth, and G. Thayer. 1994b. Monitoring of pesticides in surface waters of Florida Bay and adjacent agricultural watersheds: implications for future management of freshwater inputs into Florida Bay. Interim report. NMFS, Charleston, South Carolina.

Scott, G.I., M.H. Fulton, P.B. Key, E.F. Wirth, G. Thayer, and G.T. Chandler. 1995a. Monitoring of pesticides and other chemical contaminants in surface waters, sediments and biota of Florida Bay and adjacent terrestrial watersheds: an ecotoxicological assessment of endosulfan and other contaminants which are potential endocrine hormone mimics on estuarine and benthic organisms. Proposal to NOAA Florida Bay Program. NMFS, Charleston, South Carolina.

Scott, G.I., M.H. Fulton, J.R. Kucklick, and G. Thayer. 1995b. An ecotoxicological assessment of pesticide and urban nonpoint source runoff into Florida Bay and surrounding environments. Pages 34-35 *in* R.J. Brock, J.C. Cato, and W. Seaman, organizers. Florida Bay Science Conference: A Report by Principal Investigators, October 17 & 18, 1995, Gainesville, Florida. Abstracts and program. NPS, NBS, NOAA, USGS, FWS, COE, FKNMS, FDEP, and SFWMD.

Serafy, J. 1995. Sampling of epibenthic fish and decapod assemblages in Biscayne Bay. Project summary. UM, Miami, Florida.

Shahane, A.N. 1994. Pesticide detections in surface waters in Florida. Pages 408-416 *in* A.R. Dutton, editor. Toxic Substances and the Hydrologic Sciences. American Institute of Hydrology, Minneapolis, Minnesota.

Shaw, S.L., A.A. Schulman, and P. Lutz. 1994. The effect of Hurricane Andrew on a monitored *Caretta caretta* nesting beach. Pages 170-171 *in* B.A. Schroeder and B.E. Witherington, editors. Proceedings of the Thirteenth Annual Symposium on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-341. NMFS, Miami, Florida.

Sheridan, T. 1994. Price hikes won't stop sales. February 13, 1994. The Miami Herald, Miami, Florida.

Shine, M.J., D.G.J. Padgett, and W.M. Barfknecht. 1989. Ground water resource assessment of eastern Palm Beach County, Florida. Technical Publication 89-4, Part I (text) and Part II (plates and oversized appendices). SFWMD, West Palm Beach, Florida.

Shultz, R. 1991. Population growth and migration: southeast Florida in regional context. Pages 43-61 *in* T.D. Boswell, editor. South Florida: The Winds of Change. Annual Conference, Association of American Geographers, Miami, Florida.

Simpson, C.H. 1929. The Florida tree snails of the genus *Liguus*. Proceedings of the U.S. National Museum 73:1-44.

Skinner, R.H., and W. Kandrashoff. 1988. Abnormalities and diseases observed in commercial fish catches from Biscayne Bay, Florida. Water Resources Bulletin 24:961-966.

Small, J.K. 1918. Botanical exploration in Florida in 1917. Journal of the New York Botanical Garden 28:1-20, 25-40.

Snyder, J.R. 1986. The impact of wet season and dry season prescribed fires on Miami rock ridge pineland, Everglades National Park. Report SFRC-86/06. SFRC, ENP, Homestead, Florida.

Snyder, J.R., A. Herndon, W.B. Robertson Jr. 1990. South Florida rockland. Pages 230-277 (Chapter 8) *in* R.L. Meyers and J.J. Ewel, editors. Ecosystems of Florida. University of Central Florida Press, Orlando, Florida.

South Florida Regional Planning Council. Undated. A regional profile. SFRPC, Hollywood, Florida.

South Florida Regional Planning Council. 1989. Southwest Broward/ Northwest Dade subregional study, phase 1. SFRPC, Hollywood, Florida.

South Florida Regional Planning Council. 1990. Southwest Broward/ Northwest Dade subregional study, phase 2. SFRPC, Hollywood, Florida.

South Florida Regional Planning Council. 1991. Regional Plan for South Florida. Rule 29J-2.007 Florida Administrative Code. SFRPC, Hollywood, Florida.

South Florida Water Management District. Undated(a). Exhibit "A," statement of work, South Dade County Watershed Project (C-5245). SFWMD, Miami Service Center, Miami, Florida.

South Florida Water Management District. Undated(b). How to xeriscape. Brochure. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. Undated(c). Desalination: an additional water source for South Florida. For Your Information pamphlet. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. Undated(d). Xeriscape Plant Guide II. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. Undated(e). Xeriscape Learning Center, self-guided tour. Brochure. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1982a. An analysis of water supply backpumping for the Lower East Coast planning area. Special report (revised) DRE-137. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1982b. Report on Tropical Storm Dennis, August 16-18, 1981. Water Resources Division, Resource Planning Department, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1984a. North New River backpumping water quality impact study report #1, preconstruction and initial operation. Technical Memorandum. Water Chemistry Division, Resource Planning Department, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1984b. Water management planning for the western C-51 basin. DRE 178. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1987. Western C-51 basin, Palm Beach County population and land use projections (1985-2040). Water Use Planning and Management Division, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1992. Dade County-Florida Keys water supply background document. Draft report and appendices. Planning Department, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1993. Working document in support of the Lower East Coast Regional Water Supply Plan. Draft report, appendices, and technical information. Planning Department, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1994a. District Water Management Plan. Planning Department, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1994b. Request for proposals (RFP), Hispanic leadership campaign. Issue date March 15, 1994. Procurement and Contract Administration, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1995. South Florida Ecosystem Restoration Plan. November 1995. SFWMD, West Palm Beach, Florida.

Steinberg, B. 1980. Vegetation of the Atlantic Coastal Ridge of Broward County, Florida based on 1940 imagery. Florida Scientist 43:7-12.

Stone, T., and D. Suman. 1995. Miami's bay-bottom burden: the Biscayne Bay sewage pipeline. Pages 110-132 *in* D. Suman, M. Shivlani, and M. Villanueva, editors. Urban Growth and Sustainable Habitats: Case Studies of Policy Conflicts in South Florida's Coastal Environment. Division of Marine Affairs and Policy, RSMAS, Miami, Florida.

Stone & Webster Engineering Corporation and Geraghty & Miller, Inc. 1988. 10-year Drinking Water Supply and Treatment Plan, City of Hollywood, Florida. Volume I. Draft.

Storch, W.V. 1975. South Florida's water resource - use and management. Florida Scientist 38(Suppl.1):18 (abstract).

Stronge, W. 1991. The Southeast Florida economy. Pages 70-86 *in* T.D. Boswell, editor. South Florida: The Winds of Change. Annual Conference, Association of American Geographers, Miami, Florida.

Symons, J.M., T.A. Bellar, J.K. Carswell, J. DeMarco, K.L. Kropp, G.G. Robeck, D.R. Seeger, C.J. Slocum, B.O. Smith, and A.A. Stevens. 1975. National organics reconnaissance survey for halogenated organics. Journal of American Water Works Association 67:634-647.

Tanfani, J. 1994. Commission rejects bid for 4,000 homes. February 1994. The Miami Herald, Miami, Florida.

Tarnow, J. 1969. Population control in South Florida. Pages 44-46 *in* W.R. McCluney, editor. The Environmental Destruction of South Florida. University of Miami Press, Coral Gables, Florida.

Taylor, K. 1991. Living treasures of Florida's tropical hardwood hammocks. Wild Florida, Volume 2: Florida's unique natural areas, tropical hardwood hammock. Pamphlet. Nongame Wildlife Program, FGFWFC, Tallahassee, Florida.

Teas, H.J. 1974. Mangroves of Biscayne Bay. Report to the Metropolitan Dade County Commission, Miami, Florida.

Teas, H.J. 1976. Productivity of Biscayne Bay mangroves. Pages 103-112 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Teas, H.J. 1977. Ecology and restoration of mangrove shorelines in Florida. Environmental Conservation 4:51-58.

Teas, H.J., H.R. Wanless, and R. Chardon. 1976. Pages 133-156 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Teets, T., S. Krupa, et al. 1991. Broward County Water Supply Plan, Phase I. SFWMD, West Palm Beach, Florida.

Thayer, D., and A. Ferriter. 1994. Invasive non-indigenous vegetation management on South Florida Water Management District lands. Pages 146-157 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

The Nature Conservancy. 1994. Land protection highlights. Florida Chapter News, Summer 1994. The Nature Conservancy, Florida Chapter, Winter Park, Florida.

Thomas, M.C. 1994. Insect immigrants indirectly attributable to Hurricane Andrew. Pages 54-55 *in* An Assessment of Invasive Non-Indigenous Species in Florida's Public Lands. FDEP, Tallahassee, Florida.

Thorhaug, A. 1976. The vascular plants of Biscayne Bay. Pages 95-102 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Thorhaug, A., M.A. Roessler, and D.C. Tabb. 1976. Man's impact on the biology of Biscayne Bay. Pages 301-312 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Town of Palm Beach. 1993. Mid-Town PEP Reef sea turtle monitoring study, April 19 - October 5, 1993. Town of Palm Beach, Palm Beach, Florida.

Trimble, P. 1986. South Florida Regional Routing Model. Technical Publication 86-3. SFWMD, West Palm Beach, Florida.

Tropical Audubon Society. 1994. Green pockets in urban sprawl may serve as wildlife "lifeboats." Tropical Audubon Bulletin 1994(April):4.

U.S. Army Corps of Engineers. 1992. Part V, Supplement 54, Detail Design Memorandum Addendum 2 (revised), Canal 51 - west end, control structures 155A, 360, pumping station 319 and levee 85. C&SF Project, COE, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1993. Experimental program of water deliveries to Everglades National Park, Taylor Slough iteration. Final environmental assessment. C&SF Project, COE, Jacksonville District, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1994. Canal 111 (C-111) South Dade County, Florida. Final integrated general reevaluation report and environmental impact statement. C&SF Project, COE, Jacksonville District, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1995a. Manatee Protection Plan (part 1) at selected navigation & water control structures in central and southern Florida. Draft project modification report and environmental assessment. C&SF Project, COE, Jacksonville District, Jacksonville, Florida.

U.S. Army Corps of Engineers. 1995b. Updated reconnaissance report, Biscayne Bay, Florida. COE, Jacksonville District, Jacksonville, Florida.

U.S. Army Corps of Engineers and South Florida Water Management District. 1995. Comprehensive review study including water preserve areas. Project study plan draft version 3.0. Central and Southern Florida Project. COE, Jacksonville District, Jacksonville, Florida.

U.S. Senate. 1911. Everglades of Florida (Acts, Reports, and Other Papers, State and National, Relating to the Everglades of the State of Florida and their Reclamation). Senate Doc. No. 89, 62nd Congress, 1st Session. GPO, Washington, D.C.

University of Miami. 1995. Red drum Biscayne Bay Stock Enhancement Program. Information summary. Experimental Hatchery, RSMAS, Miami, Florida.

University of Miami and Florida International University. 1992. The New South Dade Planning Charrette: from adversity to opportunity. UM School of Architecture and FIU School of Design Miami, Florida.

Van Lent, T.J., R. Johnson, and R. Fennema. 1993. Water management in Taylor Slough and effects on Florida Bay. Technical Report 93-3. SFRC, NPS, Homestead, Florida.

Van Meter, V.B. 1987. Florida's alligators and crocodiles. Prepared for Florida Power & Light Company, Miami, Florida.

Voss, G.L. 1976. The invertebrates of Biscayne Bay. Pages 173-179 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Voss, R.S. 1976. Observations on the ecology of the Florida tree snail, *Liguus fasciatus* (Müller). The Nautilus 90(2):65-69.

Wade, D., J. Ewel, and R. Hofstetter. 1980. Fire in South Florida ecosystems. U.S. Forest Service General Technical Report SE-17. Southeastern Forest Experiment Station, Asheville, North Carolina.

Waite, T.D. 1976. Man's impact on the chemistry of Biscayne Bay. Pages 279-285 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Waite, T.D., and L. Greenfield. 1977. Stormwater runoff characteristics and impact on urban waterways. Florida Scientist 40:239-249.

Walker, R.T., and W.D. Solecki. 1994. Encroachment and land use change in biosphere reserve regions. Paper presented at the Human Dominated System Directorate of U.S. MAB Program Workshop, January 5-7, 1994, Miami, Florida. HDS-GIS Specialty Group, Department of Geography, FSU, Tallahassee, Florida.

Waller, B.G. 1978. Effects of land use and water management on water quality in the western South New River Canal basin, Southeast Florida, 1974-75. Water-Resources Investigation 78-30. USGS, Miami, Florida.

Waller, B.G. 1982. Effects of land use on surface-water quality in the East Everglades, Dade County, Florida. Water-Resources Investigation 81-59. USGS, Tallahassee, Florida.

Waller, B.G. 1983. Effects of land use on ground-water quality in the East Everglades, Dade County, Florida. Water-Resources Investigations 82-4093. USGS, Tallahassee, Florida.

Waller, B.G., B. Howie, and C.R. Causarás. 1987. Effluent migration from septic tank systems in two different lithologies, Broward County, Florida. Water-Resources Investigations Report 87-4075. USGS, Tallahassee.

Waller, B.G., H. Klein, and L.J. Lefkoff. 1984. Attenuation of stormwater contaminants from highway runoff within unsaturated limestone, Dade County, Florida. Water-Resources Investigations Report 84-4083. USGS, Tallahassee, Florida.

Walters, R.R. 1987. Dade County, Florida, case study. Pages 205-239 *in* G.W. Page, editor. Planning for Groundwater Protection. Academic Press.

Wanless, H.R. 1976. Man's impact on sedimentary environments and processes. Pages 287-299 *in* A. Thorhaug, editor. Biscayne Bay: Past/Present/Future. UM Sea Grant Program, Coral Gables, Florida.

Wedderburn, L.A., S.M. Trost, and J. Lane. 1981. Management of water levels in the "Frog Pond" Area, South Dade County, Florida. Technical Publication 81-4. SFWMD, West Palm Beach, Florida.

Weinberg, M., D. Reece, and D. Allman. 1980. Effect of urban stormwater runoff to a man-made lake on groundwater quality. Technical Publication 80-4. SFWMD, West Palm Beach, Florida.

Wershoven, J.L., and R.W. Wershoven. 1992a. Juvenile green turtles in their nearshore habitat of Broward County, Florida: a five year review. Pages 121-123 *in* M. Salmon and J. Wyneken, editors. Proceedings of the Eleventh Annual Workshop on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-302. NMFS, Miami, Florida.

Wershoven, R.W., and J.L. Wershoven. 1989. Pages 185-187 *in* S.A. Eckert, K.L. Eckert, and T.H. Richardson, editors. Proceedings of the Ninth Annual Workshop on Sea Turtle Conservation and Biology. NOAA Technical Memorandum NMFS-SEFSC-232. NMFS, Miami, Florida.

Wershoven, R.W., and J.L. Wershoven. 1992b. Stomach content analysis of stranded juvenile and adult green turtles in Broward and Palm Beach counties, Florida. Pages 124-126 *in* M. Salmon and J. Wyneken, editors. Proceedings of the Eleventh Annual Workshop on Sea Turtle Biology and Conservation. NOAA Technical Memorandum NMFS-SEFSC-302. NMFS, Miami, Florida.

Whalen, P.J., and M.G. Cullum. 1988. An assessment of urban land use/stormwater runoff quality relationships and treatment efficiencies of selected stormwater management systems. Technical Publication 88-9. SFWMD, West Palm Beach, Florida.

Wheeler, R.J. 1990. Behavioral characteristics of squirrel monkeys at the Bartlett Estate, Ft. Lauderdale. Florida Scientist 53:312-316.

Wilson, L.D., and L. Porras. 1983. The ecological impact of man on the South Florida herpetofauna. Special Publication No. 9. University of Kansas Museum of Natural History, Lawrence.

Winsberg, M.D. 1991. South Florida agriculture. Pages 17-30 *in* T.D. Boswell, editor. South Florida: The Winds of Change. Annual Conference, Association of American Geographers, Miami, Florida.

Witherington, B.E. 1990. Low pressure sodium vapor lighting and hatchling orientation. Unpublished report submitted to City of Delray Beach. As referenced in Fletemeyer 1991.

Wolf, R.E. 1989. Boca Raton sea turtle protection program (1988) in conjunction with the North Beach Nourishment Project. Page 191 *in* S.A. Eckert, K.L. Eckert, and T.H. Richardson, editors. Proceedings of the Ninth Annual Workshop on Sea Turtle Conservation and Biology. NOAA Technical Memorandum NMFS-SEFSC-232. NMFS, Miami, Florida.

Wood, D.A. 1994. Official lists of endangered and potentially endangered fauna and flora in Florida. FGFWFC, Tallahassee, Florida.

Wood, P.R., D.F. Jackson, J.A. Gervers, D.H. Waddell, and L. Kaplan. 1980. Removing potential organic carcinogens and precursors from drinking water. Volume I and Appendix A. EPA-600/2-80-130a. Municipal Environmental Research Laboratory, EPA, Cincinnati, Ohio.

Wood, P.R., , F.Z. Parsons, R.F. Lang, I.L. Payan, S.S. E.-Tracey, H.J. Harween, D.H. Waddell, R.A. Coates, R.D. Diaz, M.S. Goldberg, and F.W. Curtis. 1984. Pilot plant project for removing organic substances from drinking water. EPA-600/2-84-009. Municipal Environmental Research Laboratory, EPA, Cincinnati, Ohio.

Woodall, S.L. 1980. Integrated methods for melaleuca control. Pages 135-140 *in* R.K. Geiger, compiler. Proceedings of *Melaleuca* Symposium, September 23-24, 1980. FDACS, Division of Forestry, Tallahassee, Florida.

Yan, J.J., C. Bevier, K.A. Smith. 1995. Revision and recalibration of the three-dimensional ground water flow model of Palm Beach County, Florida. Technical Memorandum DRE-322. SFWMD, West Palm Beach.

Yoder, D. 1993. Status report on environmental studies, Lake Belt contract. Summary prepared for J. Browder, 11/8/93. Dade County DERM, Director's Office, Miami, Florida.

Yoder, D., J. Baker, P. Church, J. Rodriguez, and A. Clemente. Undated. Dade County's plan for aquifer management. Dade County DERM, Miami, Florida.

Young, E. 1994. South Dade Wetlands Acquisition Project: ownership, assessed value, and vulnerability summary, and map. Metro-Dade EELAP, Office of the County Manager, Miami, Florida.

Young, E. 1995. Acquisition projects: Environmentally Endangered Lands Program, list and map, February 1995. Metro-Dade EELAP, Office of the County Manager, Miami, Florida.

Zaneski, C.T. 1994a. Wetlands may have a place in Wayne's World. May 2, 1994. The Miami Herald, Miami, Florida.

Zaneski, C.T. 1994b. Wildlife pays ultimate price for Florida's green fairways. July 11, 1994. The Miami Herald, Miami, Florida.

Zaneski, C.T. 1995. Golf greens pesticide limited for wildlife's sake. July 7, 1995. The Miami Herald, Miami, Florida.

Zapolsky, S. 1993. Ecological Sustainability and Human Institutions Project HDS-GIS data dictionary. Department of Geography, FSU, Tallahassee, Florida.

APPENDIX

SCIENCE SUMMARIES

SUBREGION 9

This appendix summarizes many of the science, restoration, and evaluation projects that have been conducted or initiated to address ecosystem issues in the LEC. Generally, the projects in this appendix are limited to those conducted over the past 20 years. Earlier surveys and projects are discussed in the background section of the LEC chapter. The projects are categorized by topic as listed below. Within each topic, projects are organized under four headings: Palm Beach County, Broward County, Dade County, and Subregion. The Subregion category contains programs that cover more than one county; these may be regional, state, or national programs that include the LEC. Under each heading, projects are organized by the agency or organization conducting them. They are generally organized in order of: Federal, State, regional, county, and municipal agencies; universities; nongovernmental organizations; and business. This appendix does not contain a separate bibliography; the cited references are included in the chapter bibliography.

The body of knowledge on the LEC is vast and is not itemized in complete detail. For instance, all the extensive studies on Biscayne Bay are not described individually (see more than 1700 citations in Hale 1993), nor is every applicable study from the wealth of county/municipal, SFWMD, or USGS literature. Also, only a few programs are listed as examples under Science Information Transfer, while it is realized that almost every government and nongovernmental environmental organization in the urban area has programs related to information transfer and environmental education.

WATERSHED HYDROLOGY/WATER SUPPLY/STORMWATER 427

WELLFIELDS/GROUNDWATER QUALITY 435

SURFACE WATER/SEDIMENT QUALITY 440

AIR QUALITY 447

HABITAT/NATURAL AREA RESTORATION/MITIGATION 448

BIOTA/PROTECTED SPECIES 461

SCIENCE INFORMATION TRANSFER 469

WATERSHED HYDROLOGY/WATER SUPPLY/STORMWATER

Palm Beach County

COE

Evaluation of flood management for west C-51 basin. The principal alternative evaluated was construction of a detention area east of the northeast corner of WCA 1. Water would be pumped from C-51 into the detention area, stored for a short period of time, and released back into C-51 later when the canal system could deal with the water. The plan would tend to moderate extreme salinity fluctuations in Lake Worth by reducing peak discharges of fresh water. Two other alternatives (building a detention area inside WCA 1 and discharging stormwater directly into WCA 1) would have unacceptable adverse environmental impacts. The alternative of no action is also unacceptable because of extensive damage that will occur. (COE 1992)

SFWMD

Groundwater flow model. A three-dimensional groundwater flow model of the Surficial Aquifer System in eastern Palm Beach Co. was developed in 1989. Two originally separate models for the northeast and southeast county were combined into a single model that incorporates portions of Broward and Martin counties. The model performs on a monthly time step a continuous yearly simulation using historical data including pumpage, rainfall, and evapotranspiration. The model is used for predictive purposes; e.g. to determine water demands of the Lake Worth Drainage District. The Palm Beach models were among the first developed as part of the SFWMD program to quantify water resources. The process includes periodic revision and recalibration. The Palm Beach models are the first to be updated. (SFWMD 1993; Shine et al. 1989; Yan et al. 1995)

Determination of drawdown zones of influence. This study defined areas of possible surface water impacts due to permitted withdrawals from existing municipal water supply wellfields. Maps were produced showing 1-ft drawdown lines. Several wellfields were hydraulically connected to large surface water bodies or canals. (Padgett 1987)

Preliminary feasibility study of a wastewater reuse system for Palm Beach Co. A SFWMD evaluation found that Palm Beach Co. had the largest potential reuse size of any county in its district. Eastern Palm Beach Co. was selected for a case study because of its large population, ample supply of wastewater, and large potential demand (i.e., numerous golf courses and large landscape areas). A design and cost analysis described existing suppliers, existing users, design and cost of the network needed to link them, and necessary treatment system. The study indicated only 13 of 84 potential users would find the system cost-effective. Few existing treatment plants or irrigation users would voluntarily participate in a wastewater reuse system because it would not be economically advantageous. (Adams et al. 1984)

Evaluation of floodwater management in C-51 basin. Alternatives were examined for improving water management conditions in western Palm Beach Co. to protect existing development from flood damages, determine impacts of improved management on flood conditions, and determine impacts of backpumping on environmental resources. Although the pollutant load to Lake Worth would be reduced, a potential problem with backpumping is pollutants discharged to the WCA from use of pesticides in the basin and also the practice of using sewage sludge on pastures and citrus groves. (C&SF FCD 1973; SFWMD 1984b)

Efficiency of surface water management system at commercial site. A study at Boynton Beach Mall investigated water quality and quantity interactions associated with a wet detention system of three interconnected ponds that discharged into a local drainage canal. The system was found to be an effective means of reducing stormwater nutrient mass loads entering receiving waters. (Holler 1989)

Timbercreek Subdivision stormwater monitoring. This single-family residential development in Boca Raton has a drainage system of grass swales, catch basins, storm sewers, and an interconnected system of detention lakes. Data were collected to assess methodologies used to compute ground storage and runoff volumes, structure performance compared to theoretical values, detention lake performance, and water quality improvement. Levels

of seepage into the surface lakes resulting from storm-induced elevated groundwater levels were higher than expected. Groundwater-surface water interactions require additional analysis. The swale-lake system provides significant removal of suspended solids and dissolved nutrients from runoff. It also provided excellent attenuation of the runoff hydrograph. (Cullum 1984; Gregg 1984)

Modeling rainfall runoff. A system integrating a hydrologic model and a hydraulic routing model was developed that addresses the flat topography and complex canal networks of South Florida. The models were applied to the Hillsboro Canal basin in Palm Beach and Broward counties, as part of an ongoing COE flood control study in the basin. (Obeysekera et al. 1993)

Palm Beach Co. Area Planning Board

Stormwater study design. This was a 1-year study to develop a cost-effective method of controlling stormwater runoff pollution. Included were a review of runoff pollution problems, evaluation of control techniques, and effects of runoff on receiving waters. (Area Plan. Bd. Palm Beach Co. 1974)

Broward County

USGS/FDOT/FDER/Broward Co.

Stormwater runoff quality from three land-use areas. Stormwater studies were done during 1974-78 on a single-family residential site, commercial site, and highway site. Synchronized data were collected for rainfall, stormwater discharge, water quality, and bulk precipitation quality. Analysis showed that most runoff was from impervious areas hydraulically connected to drain inlets. One residential area yielded the largest loads of nitrogen, phosphorus, and dissolved solids. The commercial area yielded the largest loads of lead, zinc, and chemical oxygen demand. (Mattraw et al. 1978a; Mattraw and Miller 1981; Mattraw and Sherwood 1977; Miller and Mattraw 1982)

USGS/Broward Co. Water Resources Management Division

Effects of highway runoff on Biscayne Aquifer. Two sites adjacent to heavily traveled highways were studied during 12 storms in 1983 to determine if stormwater percolating through unsaturated sand underlying vegetated swales affects quality of water in the surficial Biscayne Aquifer. There was significant near-surface accumulation of trace metals (iron, lead, zinc), but chemical attenuation of the percolate with depth resulted in no obvious water-quality effects on the aquifer. (Howie and Waller 1986)

SFWMD

Water supply plan for Broward Co. In Phase I, SFWMD described water supply goals, policies, and issues; compiled data; and conducted preliminary analysis. The issues considered were regional system supply availability, water supply and demand management alternatives, surface water recharge alternatives, future demand projections, saltwater intrusion, wetlands and environmentally sensitive areas, treatability/drinking water standards, groundwater contamination, and long-term water supply planning. The general recommendation was Broward needed to look at multiple sources for future water supply, including development of alternatives such as wastewater reuse, aquifer storage and recovery, reverse osmosis and backpumping. This diversification would allow it to reduce dependence on the regional surface water system for supplemental water supply. In 1991, SFWMD was conducting a cooperative analysis with Broward Co. on feasibility and implementation for wastewater reuse county wide. A cooperative study of the Hillsboro basin was ongoing with COE that, while focused on flood control, also analyzed water supply availability that could result from backpumping options. Several reuse projects were in various stages of planning or implementation. Pompano Beach was reusing up to 2.5 MGD of effluent from one ocean outfall. South Broward Utilities was reusing wastewater through a multicell percolation pond system for groundwater recharge. One Broward Co. regional plant and the City of Hollywood were developing reuse projects. Hollywood was also investigating feasibility of using treated wastewater as a hydrodynamic salinity control barrier. SFWMD was also evaluating treatability of water from the Upper Floridan Aquifer. Hollywood and Hallandale were also

evaluating feasibility of using the Upper Floridan Aquifer and membrane treatment technology to expand public water supplies. (Teets et al. 1991)

Groundwater flow model. A three-dimensional groundwater flow model of the Surficial Aquifer System in eastern Broward was developed in 1992. The model performs on a monthly time step a continuous yearly simulation using historical data including pumpage, rainfall, and evapotranspiration. The model is to be used for predictive purposes; e.g., evaluating potential impacts of the proposed Broward North Regional Wellfield, and of the City of Deerfield Beach and Broward 2A wellfields and their combined impact on the saline interface. (SFWMD 1993; Restrepo et al. 1992)

GIS for Western C-9 basin. A design workshop held in 2/95 addressed suburban sprawl in the basin, which includes parts of south Broward and north Dade, and its effects on water resources. A GIS allowed diverse information to be readily available to accelerate compilation of a plan that brought together common interests of the participants. The project's success means it can be a model for addressing conflicts between development and water resource protection in other parts of South Florida. (Biggs and Saari 1995)

Broward Co. DNRP

Stormwater monitoring program. This was implemented to fulfill requirements of EPA's NPDES program. A stormwater program is also proposed to monitor environmental degradation associated with industrial activities in and around Fort Lauderdale International Airport. (Frazel 1994)

Joint Center for Environmental and Urban Problems

Analysis of use of a deep lime-rock pit as a natural advanced wastewater treatment and groundwater recycling facility. An evaluation was conducted of the condition of a privately owned rock pit after 20 years of receiving groundwater, drainage, and tertiary-treated effluent. Included were studies on recycling organic waste by *Tilapia*, on phytoplankton biomass, and on virus survival. This appeared to provide an inexpensive, safe, and practical drainage and wastewater treatment and inactivation facility that stored and recycled stormwater and wastewater instead of discharging it to the New River. (Burney et al. 1991)

Dade County

COE/EPA/Dade Co. DERM

Lake Belt environmental studies. COE is collecting information needed to prepare an Environmental Impact Statement on the Dade Freshwater Lake Belt proposal. EIS studies began in 1993. EPA has the lead for developing water quality information and is assessing adequacy of existing data, conducting sampling and analysis to complete a water quality assessment, and identifying potential impacts. Initial sampling for sediment and water quality and biogeochemical processes took place in spring and early summer 1995. DERM is conducting habitat evaluation and ecology studies, including evaluation of existing function and quality of freshwater wetlands within the Lake Belt study area. A comprehensive 2-year ecological evaluation of existing lake, littoral, and canal areas is being done by Nova Southeastern Univ.; existing vegetation and soil conditions are being mapped by EAS Engineering; and quantitative data are being collected on wildlife populations in the area by Everglades Research Group. Data will be used to analyze future environmental conditions under various scenarios involving excavation of deepwater lakes and protection and enhancement of adjacent wetlands. The University of Miami is developing a research plan for study of melaleuca in the Lake Belt, including determining the best approach to measure evapotranspiration for input to hydrologic models. The South Florida Water Management Model is being used to evaluate impacts to the environment and urban water supply. A Dade Co.-specific integrated groundwater-surface water flow model is being developed to determine local implications of alternative configurations of the Lake Belt. (G. Miller, EPA, pers. comm.; NW Dade Freshw. Lake Plan Implem. Comm. 1995; Nova Univ. 1995; Yoder 1993)

COE/USGS/SFWMD

Biscayne Bay hydrology. In a cooperative project, USGS is measuring and calibrating freshwater discharges into Biscayne Bay from 12 Dade Co. canals. Under the Survey Review Program, COE will develop a salinity model and analyze freshwater flows to the bay, with the objective of characterizing and restoring the hydrological regime to BNP. (SFWMD 1995)

USGS/SFWMD/Dade Co.

Stormwater runoff data from a multifamily residential area. Loads for 19 water quality constituents were computed for runoff from an apartment complex during 206 rainfall events from May 1977-June 1978. (Hardee and Mattraw 1979)

SFWMD

Water supply information for Dade Co.-Florida Keys. Available information on supply and use of local water resources and its relationship to SFWMD's water supply system was compiled and evaluated, including: description of relevant water supply goals, directives, and policies as they apply to water supply planning in Dade and Monroe; compilation and preliminary analysis of extensive data available on the area's water resources; analysis to quantify present and future water demands, water use, and constraints on future water supply sources; and a preliminary analysis of water supply and conservation options. This information was collected to develop a water supply plan for the Dade-Florida Keys area. (SFWMD 1992)

Groundwater flow model. A three-dimensional groundwater flow model of the Surficial Aquifer System in eastern Dade is being developed. The model performs on a monthly time step a continuous yearly simulation using historical data including pumpage, rainfall, and evapotranspiration. The model is to be used for predictive purposes. (SFWMD 1993)

South Dade Co. Watershed Project. The UM School of Architecture, Center for Urban & Community Design, is contracted to apply watershed approach to integrate land development and resource protection by interactively coordinating local, state, and Federal planning activities. Project is first step in developing comprehensive watershed plan for restoration and protection of Biscayne Bay. Objectives are to: 1) provide comprehensive understanding of relationships between land use in South Dade and regional water management objectives; 2) build consensus among interests as to actions necessary to achieve water management objectives; and 3) select a hydrologic basin within the South Dade watershed for future study and development of demonstration project(s). A complete data inventory for the watershed will be prepared with descriptions and sources of data. Data analysis will include: 1) total existing and future wetland area; 2) total area by existing and future land use; 3) estimate of existing and future stormwater pollutant loadings; 4) estimate of existing and future total impervious area; 5) feasibility of using wetlands for pollution load and ranking of potential restoration sites; 6) feasibility of using urban stormwater BMPs for pollution load; 7) estimate of existing and future water storage capacities; 8) evaluation of nonstructural alternatives. A summary report will establish impact of South Dade land use on regional water management objectives, recommend strategies for achieving those objectives in South Dade, and recommend a hydrologic basin within South Dade for future study. One idea is to reconfigure and revegetate existing canals to better integrate them into the ecological landscape. (SFWMD undated(a); Alleman et al. undated)

Miami-Dade WASAD

Wastewater reuse feasibility study. WASAD conducted a feasibility study as mandated by State law. Uses for reclaimed water investigated were urban irrigation, agricultural irrigation, wetland application, aquifer recharge, saltwater barrier, power plant reuse, industrial reuse, and potable reuse. Technically, reuse is feasible. A minimal level of reuse is most technically feasible because of permitting and implementation concerns associated with agricultural and some other alternatives. All alternatives provide environmental benefits, including conserving potable water, postponing expansion of water supply, recharging aquifers, improving surface water quality, and saving fertilizer due to nutrient content of reclaimed water. Contractor recommendation was to proceed with an aggressive reuse program based on a "medium" reuse alternative consisting of 120 mgd of public access reuse

(parks, golf courses, campuses, sports fields, agricultural lands), 30 mgd of saltwater intrusion control in the Central District by recharge of Snake Creek Canal, and 39 mgd of saltwater intrusion control in the South District by injection or wetlands restoration. Major concerns with reuse are vulnerability of the Biscayne aquifer to pollutants discharged on land surface, and effluent from the Central and North District treatment plants has elevated chloride concentrations that could negatively impact irrigation reuse. Application of reclaimed water to wetlands might restore hydrologically altered communities or create wetlands on former wetland sites. The site with the greatest potential for wetland restoration was in South Dade in the Model Lands basin. (PBSJ 1992)

Dade Co. DERM

Stormwater monitoring program. Under EPA's NPDES program. A survey of all outfalls (Phase I) began around 1990. Phase II began in July 1992 with 12 sites in Dade sampled during three rain events per year. Each site is representative of a certain land use or combination of uses. These include transportation, sales and services, multifamily, single-family, golf course, shopping center, and industrial. Results are compared to those obtained through EPA's National Urban Runoff Program. The total number of outfalls is nine times the number of major outfalls. Quantitative data to date indicate control efforts should be placed on control of total number of outfalls of smaller diameter, rather than on major outfalls alone. Biomonitoring is also done as specified in the NPDES permit. (A. Rodriguez, DERM, pers. comm.; R. Rodriguez, DERM, pers. comm.; Rodriguez 1994; D. Valdes, DERM, pers. comm.)

Modeling of point source discharges. Concentrations and loadings of various pollutants present in point source discharges have been modeled for all of the more than 4,000 stormwater outfalls in the county. DERM has a database of all existing outfalls and related information. A model developed using results of the NPDES program can be calibrated to produce annual, seasonal, or monthly loadings. (R. Rodriguez, DERM, pers. comm.)

Stormwater impact assessment. DERM has proposed to EPA to proceed with a comprehensive evaluation of canal surface waters and sediments to evaluate runoff impact on receiving waters. Sampling will be conducted at 46 sites located at inflow points, midstream, and discharge points within major canals of each of 18 primary drainage basins. Various sets of parameters will be measured on monthly, bimonthly, quarterly, and annual schedules. Quarterly sediment samples will also be collected. [Also see Surface Water/Sediment Quality.] (A. Rodriguez, DERM, pers. comm.)

Weather monitoring. To complement the NPDES program and stations already installed by the Water and Sewer Department, DERM is installing an array of telemetered weather stations county wide. The data generated will include rainfall, wind speed and direction, temperature, and humidity. (R. Rodriguez, DERM, pers. comm.)

Dade Co. Department of Solid Waste Management

Stormwater retention pond at Dade Co. Resources Recovery Facility. A 14-acre retention pond is being built at this facility in northwest Miami, as required by COE permit, to compensate for loss of 26 acres of melaleuca-dominated wetlands associated with closure of an existing ash landfill and expansion of a new ash landfill. The project will permanently convert the area to a primarily herbaceous wetland with diverse native species. The pond will include eight acres of littoral shelf. The project is designed to be flooded at the surface for at least 9 months per year to limit establishment of melaleuca. (Danhausen 1994)

Stormwater retention basin at South Dade Landfill. The plan for landfill closure includes collection of all runoff from capped landfill cells in perimeter swales that feed into a 54-acre wetland retention basin. Stormwater will percolate into the groundwater, and no offsite discharge will be allowed. The basin will be surrounded by a 12-ft wide, 10.5-ft high dike and will be divided into three zones by a berm system to control water elevations in the zones. The wetland hydroperiod is being studied to determine optimum elevation of spillways to ensure survival of native wetland plants. The basin will include freshwater marsh and brackish water habitat, and berms will be planted with tropical hammock species. All exotic plants will be eradicated. Fish populations and recruitment will be studied in the three zones. (Danhausen 1994)

FIU/SFWMD

Coastal vegetation gradient in southeastern saline Everglades. To evaluate effects of water management practices on biological communities in the Biscayne Bay SWIM area, a survey is underway to document and interpret changes in this area since initiation of Everglades drainage. Hydrology is emphasized because the area forms an extended transition zone between the freshwater Everglades and marine Florida Bay. The study has four parts: 1) establish present vegetation-hydrology and diatom-hydrology relationships; 2) characterize present spatial gradients in vegetation and diatom assemblages; 3) reconstruct historic gradients; and 4) interpret observed changes in gradient structure. (Ross et al. 1994; SFWMD 1995)

South Florida Limestone Mining Coalition

Lake Belt Plan. In 1984, the rock mining area in west Dade was given an exemption from wetlands jurisdiction by the Florida legislature; this exemption expired in 1994. In 1990 a consortium of six rock mining companies began a 2-year study to compile information and recommend an approach to protect the area's environment and water supply, as well as provide a continuing supply of aggregate. The Northwest Dade Co. Freshwater Lake Plan proposes a system of large lakes in the mining area, including 20,000 areas of lakes added to an existing 4,000 acres and 17,000 acres as constructed littoral wetlands, recreation areas, and existing wellfields. An adjoining 13,000-acre area that is relatively pristine (74% prairie) would be preserved and maintained in natural condition. The plan proposes that by mining the area to form lakes, water storage is increased, the lakes could be used to hold backpumped stormwater, and seepage under WCA levees may be reduced. The system would form a 10-km (6-mi) buffer strip between urban areas and WCAs, stopping urban sprawl from encroaching on the Dade Northwest Wellfield, which lies in the center of the area. (Larsen Assoc. 1992)

Subregion

COE/SFWMD

Comprehensive review study. Part of the restudy of the C&SF Project will be detailed development of Water Preserve Areas along the eastern boundary levees of the Water Conservation Areas. The area projected for preserves will undergo rigorous evaluation dealing with hydraulic design, water supply, yield, environmental restoration, land suitability, and estimation of pollutant load reductions associated with backpumping. Biological surveys will be conducted in cooperation with FWS and FGFWFC. Topographic surveys and aerial photography of the areas will also be conducted. (COE/SFWMD 1995)

USGS

Water resources data collection. During each water year (October-September), USGS obtains a large amount of data on Florida water resources. Data include records of stage, discharge, groundwater levels, and water quality of streams; and stage, contents, and water quality of lakes and groundwater wells. In Subregion 9, data are from 19 surface water (canal) stations, in cooperation with many municipal, county, state, and other Federal agencies in the subregion. One station on West Palm Beach Canal and another on Miami Canal have records dating back to 1939. Since 1974, the Miami Canal station has been part of the National Stream Quality Accounting Network. Throughout Subregion 9, water level is monitored in almost 140 wells either by digital water-level recorders or satellite data collection platforms. Specific conductance and concentration of dissolved chloride are measured. (Haire and Lietz 1993; Haire and Price 1993)

Freshwater discharge to East Coast. Discharge data are being collected during 1995 in cooperation with SFWMD and COE at 20 coastal canals between C-51 in Palm Beach Co. and C-111 in Dade. The data will help quantify water availability for water supply and ecosystem restoration and help calibrate regional hydrologic models. (Gerould and Kantrowitz 1995)

Evaluation of wastewater reuse policy options. SFWMD identified potential users and suppliers of wastewater throughout its district and projected average wastewater flows for each county. Palm Beach, Broward,

and Dade counties represented 73% of the district's potential capacity for wastewater reuse; Palm Beach Co. alone represented 34%. Reuse could potentially contribute a substantial amount of additional water to the region but implementation is highly dependent on local conditions and would be economically advantageous to just a small to modest proportion of suppliers and users. (Adams et al. 1984)

SFWMD

Lower East Coast water supply plan. A working document was prepared that contained background material and preliminary evaluations of information related to supply and use of regional water resources and relationships of the regional source to localized supply systems in Palm Beach, Broward, Dade, Monroe, Collier, and Hendry counties. Evaluations are based on water supply and use, estimated demands, estimated environmental needs, and system constraints. These materials form the basis for development of a final plan that will identify preferred alternative(s) and other recommendations. (SFWMD 1993)

Analysis of water supply potential for East Coast Buffer. SFWMD retained CH2M Hill to conduct feasibility studies of using shallow marshes and reservoirs in western Palm Beach, Broward, and Dade counties to store excess waters. The studies had the overall objective to provide technical information to support SFWMD evaluations of management alternatives being analyzed under the LEC regional water supply planning process. Technical analyses included land availability and siting, surface water availability, seepage and water yield predictions, wetland hydroperiods, water quality, permitting and environmental, and economic comparisons and optimization. Conceptual designs were developed for 8 management units, using GIS, with linkages to aquifer storage and recovery wells. These units included four wetland management units to be managed for wetland hydroperiod enhancement and natural system surface water supply, one surface water reservoir managed to meet urban surface water demands, and three aquifer recharge basins to promote recharge of the Biscayne Aquifer. (CH2M Hill 1994)

Water resources modeling. The District conducts intensive modeling research and evaluation to develop the best possible regional operational policies for the LEC and other subregions of South Florida. Large-scale models of both surface and groundwater are used to quantify how modifications to the hydrological system will affect water conditions and discharges. Results help decide changes that are needed in the present system to meet future needs. The SFWMM is a regional two-dimensional, integrated surface water-groundwater model used to assess the effects of management options in a large portion of South Florida, including Palm Beach, Broward, and Dade counties. Information from this model is entered into more detailed models of the surficial aquifer systems in each of the counties. The SFRRM has been used since the late 1970s to analyze the Lake Okeechobee-LEC regional hydrologic system. (MacVicar et al. 1984; SFWMD 1993; Trimble 1986)

Identification of recharge areas. 1995 was the estimated year of completion for identification and mapping of high and prime recharge areas for the Biscayne and surficial aquifers of the LEC. After public hearings, SFWMD will adopt the designation of prime aquifer recharge areas by rule. (SFWMD 1994a)

Analysis of water supply backpumping for the LEC. The basins selected for study were the West Palm Beach Canal C-51/L-8, North New River/C-13, Snake Creek Canal C-9, and Tamiami Canal basins. Effects were assessed on hydrologic conditions, economics, water quality, and model simulation of environmental conditions in WCAs and estuaries. (SFWMD 1982a)

GIS for buffer area. As the first stage in designing the Everglades buffer, a GIS was developed based on information such as land use, National Wetland Inventory, public ownership, soils, hydrology, and exotic plants. (Gulick 1995)

Stormwater research. Because of increasing concern over stormwater runoff as a significant pollution source, SFWMD has taken an active role in stormwater research. Multiple stormwater management systems have been evaluated, and many modeling efforts have been conducted for nonpoint source pollution occurrence and control. (Whalen and Cullum 1988)

Wetland hydrology. SFWMD conducted hydrologic field investigations to define natural wetland hydroperiods and determine impacts of reduced hydroperiods (from excessive drawdowns) on various types of wetlands throughout the District to evaluate existing criteria and develop new criteria if needed to protect wetlands (Teets et al. 1991).

Joint Center for Environmental and Urban Problems

Survey of wastewater reuse systems in South Florida. This study conducted in 1985 for SFWMD identified all wastewater reuse systems in an area that included most of the State south of Ocala, gathered quantitative data on the systems and information on motivations for water reuse, and selected systems for further study. The use of wastewater was primarily an economic decision because it was a low-cost disposal method. Some of these systems were discontinued in favor of deep-well injection disposal when surface water discharge regulations became more stringent. Eight municipalities in Subregion 9 had reuse systems in operation at the time of the survey; almost all effluent was used for irrigation. (Joint Center 1985b,c,d)

WELLFIELDS/GROUNDWATER QUALITY

Palm Beach County

USGS

Survey of groundwater contamination from Lantana landfill. A geophysical reconnaissance around perimeters of 12 active and abandoned landfills in Palm Beach Co. showed a low-resistivity area along the eastern boundary of the Lantana landfill. Surveys were conducted in 1985 to determine the extent of the leachate plume. Shallow water-table wells showed a hydraulic gradient to the east; groundwater movement was from the landfill toward a lake to the east. Water quality samples were collected from 14 groundwater and 3 surface water sites. Lateral movement of leachate had occurred to a distance of 91 m (300 ft) at a depth centered at 9 m (30 ft). Some vertical movement of leachate may have occurred into the lower zone of the surficial aquifer to a depth of about 21 m (70 ft). (Russell and Higer 1988)

Water quality effects of Cross State Dump. Water quality data was gathered from 22 wells and 10 canal sites from 8/70-3/72. The dump was due to be filled in 1973. The water table in the immediate dump area sloped downward in all directions towards surrounding canals. With urbanization spreading west into the vicinity and homes and industries obtaining water supplies from the shallow aquifer, Palm Beach Co. Engineering Dept. and Dept. of Health were concerned about effects of landfill waste on groundwater supplies. Leachate did impair water quality at shallow depth in the aquifer in the immediate dump vicinity, but impairment was minimal at producing wells a quarter mile south and east of the dump. There was no indication that leachate materially affected water quality in the West Palm Beach Canal. (Schneider 1973)

Palm Beach Co. DERM

Wellfield monitoring. An ongoing program since about 1980 monitors background water quality and identifies changes in 32 groundwater wells. (Haddad et al. 1995)

Broward County

USGS

Migration of septic tank effluent. Effects of effluent migration from septic tanks in the two major surface lithologies (sand and limestone) were studied. Path and rate of effluent migration were determined by analyzing groundwater samples from multidepth wells downgradient from the tank outlets. Best indicators of effluent were chloride, sulfate, nitrate, and ammonium concentrations. Effluent was detected in sand to a depth more than 6 m (20 ft) below the outlet but was near background 15.2 m (50 ft) downgradient. Effluent was detected in limestone to depths exceeding 25 ft below the outlet and was diluted but still detectable 40 ft downgradient. (Waller et al. 1987)

EPA

Davie Landfill monitoring. Due to concern about groundwater contamination from a sludge lagoon this site was placed on the National Priority List as a Superfund site in 1983. Monitoring indicated high levels of cyanide and sulfide in the sludge lagoon. Subsequent to the Record of Decision, Broward sampled private residential wells and found high levels of vinyl chloride and provided residents with bottled water and then municipal water service. Groundwater beneath the site contained elevated contaminant levels, especially of vinyl chloride and antimony, similar to those in wastes and leachate at the site. Extensive monitoring programs were part of this evaluation. (EPA 1985a, 1994d)

Petroleum Products site monitoring. Sampling at this inactive oil processing plant in Pembroke Park identified groundwater contamination by oils, volatile organic carbons, petroleum hydrocarbons, and metals (chromium and lead). A State investigation showed that free oil (20,000 - 60,000 gal.) was present in a groundwater

plume centered on the tank farm. This site lies within the radius of influence of two major municipal wellfields (Hallandale and Hollywood). (EPA 1990d)

SFWMD

Impact of a rockpit lake on groundwater quality. A common practice associated with urbanization is digging lakes to provide fill for homesites and to receive storm runoff from the development. The study site was a lake in north Broward. For one year, water samples were collected from the lake and adjacent groundwater, lake stage and water table elevation data were collected, and runoff from three storm events was analyzed. Lake sediments were also analyzed for lead content. Results showed that storm runoff to the lake could contain high concentrations of chloride, copper, lead, and nutrients. It appeared that lead was accumulating in the bottom sediments. There was a general increase in groundwater levels of some parameters such as specific conductance downgradient from the lake, but it could not be determined that the lake was the cause of the change. (Weinberg et al. 1980)

Impacts of a proposed development. A groundwater model was used to simulate multiple configurations of a proposed development in southwest Broward. Results indicate that development and Everglades restoration can coexist and demonstrate the potential benefit of a properly planned development. (Giddings 1995)

SFWMD/FDER/Broward Co.

Groundwater monitoring. Ambient groundwater quality is monitored throughout Broward Co. in a cooperative program (Teets et al. 1991).

City of Hollywood

Quality of potential groundwater supplies. Investigations were started to develop new wellfields because of potential susceptibility to saline water intrusion during periods of low rainfall and high groundwater withdrawal and because of projected water supply shortfall. Studies involved evaluation of existing treatment facilities, development of conceptual designs of water system improvements, evaluation of other water sources for diversification of the water supply, and evaluation of chemical properties and treatment needs of water from potential sources. (Metcalf & Eddy 1992; Metcalf & Eddy/Berry & Calvin 1992; Stone & Webster/Geraghty & Miller 1988)

Dade County

USGS

Reconnaissance of agrichemicals in water from open irrigation wells. In 1993 USGS sampled 14 wells, including eight mix-load wells, in South Dade in August when several sites were fallow and again in December when fertilizer and pesticide applications are normally greatest. In August, samples from two wells showed nitrate concentrations greater than the FDEP maximum contaminant level of 10 mg/L for primary drinking water standards; the level at one site was 1600 mg/L. In December, samples from three other wells had nitrate levels above the MCL; one was above 1000 mg/L. Pesticide analyses showed several compounds above analytical detection levels; endosulfan compounds were among the most frequent. Of the 11 different chemicals detected, only three - atrazine, heptachlor expoxide, and toluene - have MCLs, and levels of these were less than their MCLS. (McKenzie 1994)

Effects of land use on groundwater quality in the East Everglades. Groundwater quality was evaluated during one extended growing season in 1978-79 at seven sites in the East Everglades area of Dade Co., in cooperation with Dade Co. Planning Department. Groundwater and soil samples were collected in four agricultural areas, two low-density residential areas, and a State park unit (now part of ENP). Land-use effects on groundwater were minimal in all areas. Soil samples from all areas but the park showed detectable levels of chlorinated hydrocarbon insecticides. The soil cover appears to accumulate agrichemicals before they enter the groundwater. (Waller 1983)

Attenuation of stormwater contaminants within unsaturated limestone. This study evaluated the capabilities of geologic materials within the unsaturated zone of the Biscayne Aquifer to attenuate stormwater contaminants from a roadway in Coral Gables. Constituents measured were lead, zinc, iron, cadmium, chromium, nickel, mercury, manganese, nitrogen, and phosphorus. At the test site, the upper 1 ft of material contained higher concentrations of lead, manganese, and zinc than greater depths. The surface material appeared to be effective in attenuating traffic-generated pollutants washing from the roadway and inhibiting them from reaching the water table. (Waller et al. 1984)

Effects of septic tank effluent. Effects of septic effluent on water quality in the Biscayne Aquifer were investigated at five sites in Dade where septic tanks had been in use for more than 15 years and tank density was four or fewer per acre. Samples were collected from two sets of multidepth wells at each site. Parameters included concentrations of coliform (total and fecal) and fecal streptococcal bacteria. High ammonia and nitrogen concentrations repetitive detection of fecal coliforms were characteristic of two 3-m (10-ft) wells that consistently indicated presence of septic tank effluent in groundwater. Highest concentration of fecal coliforms was related to stormwater infiltration rather than septic tank discharge. (Pitt 1974; Pitt et al. 1975)

EPA

Munisport Landfill monitoring. This North Dade landfill was placed on the EPA National Priority List in 1983. In 1988 investigations showed landfill leachate was moving southeast towards a State mangrove preserve on Biscayne Bay. Bioassays showed the leachate to be acutely toxic. A 1989 study evaluated emergence of leachate in surface waters of the mangrove preserve, assessed toxic effects of its mixing with surface waters, and assessed nutrient potential of it mixing with waters of the preserve and being discharged to the bay. Results established that leachate-contaminated groundwater from the landfill migrated to the preserve and mixed with tidal surface waters of the bay. The leachate contained extremely elevated concentrations of ammonia; levels of unionized ammonia, the most toxic form, exceeded those established for protecting marine life and water quality. (EPA 1990a,b,c; 1994b,c)

Biscayne Aquifer monitoring. Three hazardous waste sites on the Superfund National Priorities List were addressed as a single management unit for the remedial investigation and feasibility study because they affect the same general area of the aquifer. Many individual evaluation and monitoring studies were conducted by Dade Co., FDER, USGS, and consultants in the course of action on these sites. The sites, all in north Dade, were: 1) Varsol spill site where surface and groundwaters were contaminated by hydrocarbon spills which resulted at one time in a thick hydrocarbon layer floating on the water table in an excavated trench; 2) Miami Drum site where drum recycling contaminated soils with phenols, heavy metals, oil, grease, and pesticides; 3) 58th St. Landfill where the water table is only 2-3 ft below ground surface, and contaminants of concern were arsenic, chromium, zinc, benzene, chlorobenzene, trichloroethene, vinyl chloride, and 1,1,2,2-tetrachloroethane. (EPA 1982, 1985b,c, 1987a; Mattraw et al. 1978b)

Pepper's Steel site monitoring. This is the site of several businesses, including manufacture of batteries, fiberglass boats, painting service, heavy equipment repair, and automobile scrap operation. Contaminants identified in the soil, sediments, and groundwater include PCBs, organics, and heavy metals (lead, arsenic, cadmium, chromium, mercury, zinc, antimony, etc.). Private wells exist in the area, where the groundwater is 5-6 ft below the surface. The site is also near the Miami Canal. (EPA 1986)

Gold Coast Oil site monitoring. At this site of a facility that distilled mineral spirits and lacquer thinner and reclaimed solvents, blowdown was sprayed directly onto the ground. All wastes generated during 11 years of operation, including 2500 leaking sludge drums, were stored onsite. The site is near the Coral Gables Canal, and a private well is within 30 m (100 ft) of the site. Monitoring studies beginning in 1980 by DERM showed soil and groundwater were contaminated with volatile organics and heavy metals. The site was added to the National Priority List in 1983. (EPA 1987b)

SFWMD

South Dade agricultural pilot study. 22 wells were sampled to establish background value during months of no farming for parameters such as nutrients, major ions, metals, volatile organics, and pesticides. Results suggested that agriculture has had localized impact on the water quality of the Biscayne aquifer. Pesticides once used in the agricultural area were persistent in the groundwater. Aldrin, dieldrin, and DDT were present in excess of potable surface water standards. (Anderson 1986)

East Everglades groundwater quality monitoring study. A 2-year study was initiated to determine potential adverse water quality impacts to the Biscayne Aquifer resulting from agricultural practices in South Dade. 16 groundwater, 4 surface water stations, and 12 soil stations were sampled in the 1985-86 growing season. Stations represented both active and nonactive agricultural practices. Data indicated elevated concentrations of select inorganic and organic parameters representative of agricultural activity. Concentrations of inorganic chemical parameters were elevated in active agricultural areas compared to nonactive areas, likely reflecting use of fertilizers. Six organic pesticides (aldicarb, paraquat, atrazine, metribuzin, chlorothalonil, and permethrin) were found at 14 groundwater and surface water stations. Overall aquifer water quality in the study area, however, met established standards. Current farming practices, combined with dilution during the wet season, appear to minimize impacts on the aquifer. (Anderson and Shaw 1991)

Dade Co. DERM

Ambient groundwater monitoring program. The program was initiated in 1981 to establish baseline data and assess impacts of major land use on groundwater quality. Up to 49 wells have been sampled biannually for various parameters, and special studies have been conducted on subsets of these wells. The current network includes about 35 wells in which presence of wetland soil types accounts for major differences in background water quality between north and south Dade. (J. Baker, DERM, pers. comm.)

Wellfield protection monitoring. Most major regional wellfields have monitoring networks around the production wells (Northwest, West, Snapper Creek, Southwest, and Alexander Orr). A monitoring network is currently being installed for the Norwood-Oeffler wellfield; a network for the Winson wellfield is being planned. Monitoring frequency is quarterly and emphasizes synthetic organic contaminants and other toxics. Networks are periodically reevaluated for significant land-use changes and discovery of contaminant hot spots. Existing potential sources of contamination within wellfield areas that use large quantities of hazardous chemicals, such as agricultural facilities, are inspected more frequently and when violations occur corrective action and remediation are expedited. Other wellfield protection activities include land-use controls that prohibit siting of new sources of contamination, prioritization of sewering industrial and heavy commercial areas, density limitations on residential development in inner protection zones, restrictions on rockmining, and more stringent construction standards. (J. Baker, DERM, pers. comm.; Dade DERM 1990a,b; 1991, 1992a)

Survey of pesticides used in West Wellfield study area. A 1988 survey resulted in a list of chemicals used or projected for use on major fruits, vegetables, and nursery stock. A total of 78 different active ingredients were used or projected for use as insecticides/miticides, bactericides, fungicides, herbicides, or fumigants. 25 chemicals were commonly used and the most frequently selected when a product was needed. Some pesticides are used very frequently: an estimated 30 applications of insecticides and fungicides per year on nursery plants, 25 applications of insecticide per crop of corn, 24 applications of fungicide per crop of tomatoes; 20 applications of fungicides per crop of mangos. (Dade DERM undated(e))

Groundwater monitoring for agrichemical residues. Pesticides have been detected in groundwater during studies in agricultural areas of Dade. A study during 1985-87 sampled 39 existing monitoring wells in farmed areas, along with the public drinking water supplies of southwestern Dade to assess prevalence of chlorinated pesticides. Very low levels were detected; 81% of residues were at concentrations $< 0.1\mu g/l$. Of those $> 0.1\mu g/l$, 60% were heptachlor, which is restricted to controlling subterranean termites in structures. Most detected residues were from pesticides no longer used (DDT, endrin, dieldrin). Drinking water standards were not violated by the groundwater residues, and no pesticides were found in public water supplies. A later study also found low levels of pesticides in groundwater in the East Everglades, in addition to high levels of paraquat in one sample and of chlorothalanil

in another. Some of the highest values of agrichemicals were found in samples from open, uncased irrigation wells. In 1989, 84% of groundwater samples from agricultural areas of Dade detected the herbicide atrazine; it was found in open wells, private potable wells, and a USGS monitoring well. Highest values of nitrates in private wells are in predominately farmed areas. The Florida Keys Aqueduct Authority wellfield in South Dade has not shown elevated nitrate despite being near active row crop operations. A large tract of native pinelands surrounds the plant and covers most of the protection area, providing a zone of pristine recharge [pre-Hurricane Andrew]. (Baker 1988; Dade DERM 1991)

Groundwater monitoring in West Wellfield Interim Protection Area. Monitoring began in the WWIPA in 1990; sampling has occurred bimonthly except for minor breaks. Parameters measured include major cations/anions, nutrients, trace metals, volatile organic compounds. Pesticide monitoring is done but is infrequent, may not be synchronized with use patterns, and does not include major breakdown products. Detectable levels of endrin, aldehyde, lindane, dieldrin, and clorothalonil were found in 30% of agricultural sites sampled in the WWIPA. (Dade DERM 1991, 1992a)

FIU/Miami-Dade WASAD/Dade Co. Department of Public Health

Removal of organic substances from drinking water. Research was conducted to devise feasible and economical methodology for removing existing organic contaminants from and preventing development of potential carcinogens in Dade public water supplies. The major objective was to develop methods to reduce the amount of four THMs. Efficiency of three adsorbents in removing 19 halogenated organics and THM precursors was tested. A subsequent study evaluated the practice of ozonating water to modify the naturally occurring organics, followed by bacteria-activated carbon adsorption to remove THM precursors. This research was conducted at a pilot plant constructed at one of the Dade water treatment plants. (Wood et al. 1980, 1984).

Subregion

USGS

Water resources data collection. During each water year (October-September), the USGS obtains a large amount of data on Florida water resources. The data include records of stage, discharge, groundwater levels, and water quality of streams; and stage, contents, and water quality of lakes and groundwater wells. Throughout Subregion 9, water level is monitored in almost 140 wells either by digital water-level recorders or satellite data collection platforms. Specific conductance and concentration of dissolved chloride are measured. (Haire and Lietz 1993)

NPS

Pesticides threat to Everglades National Park. Recognizing the potential threat the widespread use of pesticides in South Florida presented to ENP, a study was conducted to document pesticide use in areas surrounding ENP and assess toxicity to wildlife of identified pesticides. Documentation of use in Dade Co., Collier Co., and the EAA was difficult because reporting of agricultural pesticide use is not required unless the material is a restricted use compound. It was found that 88 pesticides were being used in the area. Also, present programs were inadequate for assessing contamination of groundwater, surface water, or wildlife. (Scheidt 1989)

SFWMD

Ambient Groundwater Quality Network. Water quality sampling began in 1984 in an extensive network of monitor wells in all of the District's counties but Monroe. Eastern Palm Beach, Broward, and Dade counties are included in the network. Sampling in Dade and Broward is subcontracted by the District to the counties (Herr and Shaw 1989; SFWMD 1994a)

SURFACE WATER/SEDIMENT QUALITY

Palm Beach County

SFWMD

Upper and Lower East Coast Water Quality Monitoring Program. This program was initiated in 1979 and includes coastal portions of St. Lucie, Martin, and Palm Beach counties. 5 of the 16 sampling stations are south of West Palm Beach (i.e., in Subregion 9). Physical parameters and nutrients are measured monthly, major ions bimonthly, and trace metals biannually. (Germain 1994)

Palm Beach Co. DERM

Surface water quality. An ongoing program since 1980 monitors ambient water quality at 46 surface water stations. (Haddad et al. 1995)

Broward County

USGS/SFWMD

Effects of land use and water management on water quality in western South New River Canal basin. A study was conducted in the C-11 drainage basin during 10/74-12/75, prior to significant urban development, to determine: hydraulic characteristics of the western basin between S-13A and S-9; loads of nitrogen, phosphorus, and total residue entering WCA 3A; sources of chemical constituents in ground and surface water; runoff characteristics in terms of nutrient and total residue load and discharge from selected land-use areas; and expected baseline levels of chemical constituents, trace elements, insecticides, biological oxygen demand, and DO. The runoffs from an undeveloped area and a low-density residential area with some pastureland were compared. Data indicated loads and concentrations of inorganic nitrogen and orthophosphate were affected by urban and agricultural development. Other constituents were fairly uniform throughout the basin. (Waller 1978)

FDEP

Pesticide monitoring in surface water. Broward was one of eight counties sampled from 1991-1993. (Shahane 1994)

SFWMD

North New River backpumping impact study. Water quality data was collected in 1982-83 before construction and during discharge to determine localized impacts of backpumped water from the North New River Canal into WCA 3A. Water and sediment were analyzed for nutrients, routine physical/chemical parameters, trace metals, chlorinated hydrocarbon and organophosphorus pesticides, herbicides, and PCBs. A contamination problem was not demonstrated at that time. (Pfeuffer 1985; SFWMD 1984a)

Broward Co. DNRP

New River Study. This first in a series of basin assessments planned for Broward Co. was a baseline study to assess the nature and extent of water quality issues in the New River. Sampling from 6/91-12/92 collected more than 3,000 samples at 13 stations to measure 35 parameters. 10 additional stations were added in 3/92 and sampled until 1/93. The New River is one of the few naturally occurring water bodies in Broward Co. It is divided into three basins: North Fork (relatively stagnant, little tidal or freshwater input, high bacteria and nutrients, low DO); Las Olas Isles (high bacteria levels associated with inhabited moored vessels), and South Fork to Intracoastal (significant flushing, chemistry typical of groundwater). The study scope included: on-site visual survey to identify potential point source impacts; monthly sampling for general water quality parameters; bi-monthly sampling for water column metals, algae, and phytoplankton; at least two composite samples during a storm event at two outfalls for water

quality parameters, metals, organics, and pesticides; annual sampling of 13 stations for pesticides in water column; one-time sediment sampling at marine maintenance facilities; 18 samplings of sludge blanket in North Fork for metals, nutrients, organics, benthos, and biotoxicity; one-time 24-hour profile in North Fork for temperature, DO, salinity, conductivity, and pH; and aerial survey of number of moored boats in Las Olas Isles area. DNRP is preparing a New River Restoration Plan that will include methods of improving water quality and biological function. DNRP is also conducting a bioaccumulation study designed to evaluate potential health effects of eating fish and crabs caught in the North Fork; this was to be completed in spring 1994. (Broward DNRP 1993)

Surface water quality monitoring program. The program started in the early 1970s to characterize the chemical, biological, and physical composition of Broward water bodies and drainage basins so any necessary remedial measures can be focused toward improving water quality and subsequently ecological health. The Environmental Monitoring Div. samples 46 stations quarterly. Parameters include fecal and total coliform, conductivity, pH, temperature, total organic carbon, turbidity, DO, salinity, nitrate and nitrite, ammonia, total Kjeldahl nitrogen, and total phosphorus. The program needs to be expanded because the county is now the manager of Port Everglades. (Frazel 1994)

Sediment toxicity. A survey to determine the biotoxicity of sediments in the county's waterways was to be completed by 6/94. A study is proposed to assess the abilities of marine organisms to assimilate and concentrate contaminants deposited in sediments during marine industrial activities. (Frazel 1994)

Bacteria monitoring. Monitoring of bacterial levels in the Las Olas Isles area is conducted under a cooperative agreement with the City of Fort Lauderdale. (Frazel 1994)

UF

Use of biocontrol agents. Experimental introduction of a South American nematode was carried out on three Broward Co. golf courses to investigate its impact on the mole cricket population. In May 1990, about 5 billion nematodes were applied at 200,000 infective juveniles/m^2 on edges of fairways on three holes on each course. Nematode populations became established at two courses. Systematic monthly sampling over 2 years indicated reduction in mole cricket populations on treated vs. untreated fairways. Use of such biocontrol agents instead of chemical pesticides could reduce input of chemicals to the environment and also result in economic savings. (Frank 1994c)

Dade County

COE

Miami River contaminated sediment disposal alternatives. The study area was the first 8.8 km (5.5 mi) of the 32-km (20-mi) river along the existing Federal channel, downstream of the salinity dam. Deposits are surficial soils eroded and transported from a large watershed, including much of Dade, Broward, and Palm Beach counties, since the initial dredging in the 1930s. Metal concentrations in these sediments are significantly higher than in soils or marine sediments elsewhere in the Biscayne Bay system. FDEP sediment samples during 1983-84 showed elevated levels of arsenic, cadmium, mercury, lead, and silver, and the presence of pesticides and PCBs. Sampling by DERM during 1983-90 showed elevated metal concentrations in sediments at some locations, especially near industrial outfalls, and presence of organic pollutants such as hydrocarbons, pesticides, and PCBs. In 7/91 a joint COE-DERM project evaluated potential impact of dumping dredge materials at a designated offshore ocean disposal site near Miami. Bioassays indicated that Miami River sediments cause levels of mortality that exceed Federal criteria for ocean disposal, and it is necessary to develop upland disposal options. Options evaluated were mechanical and hydraulic dredging, special treatment systems for the dredged solids, and disposal sites. Criteria for evaluation of environmental impacts were: groundwater contamination, surface water contamination, air pollution, leaks/spills/ accidents, destruction of wildlife habitat/natural areas/ wetlands, loss of unique site features, permanent contamination of site, contamination of nearby vegetation or fisheries, traffic congestion, odors, noise, visual ugliness, and effects on the community (image of dumping ground, magnet for heavy industry). The recommendation was to pump mechanically dredged barge-transported materials to a diked containment area at the

north end of Virginia Key, which is currently used for dredge material from the Port of Miami. (Gulf Engineers 1993)

COE/SFWMD

Hydrodynamic model of Biscayne Bay. An updated reconnaissance study was conducted to identify a means of addressing existing problems in the bay related to water quantity, including surface and groundwater inflow and circulation patterns. It was concluded that before any recommendation could be made regarding modifications of the C&SF Project, a hydrodynamic model is needed to help understand the bay ecosystem. The study determines the technical feasibility and interest in developing and operating a hydrodynamic simulation model and other ecosystem models of the bay that are intended to assess impacts of the C&SF Project and effects of operational changes on the bay. Three phases of model development will be creation of 1) the hydrodynamic model and associated ground and surface water models, 2) a water quality model, and 3) a biological model. Dade Co. has agreed to be the non-Federal sponsor for the model development (COE 1995b; COE/SFWMD 1995)

EPA

Environmental Monitoring and Assessment Program. In 1995, Biscayne Bay was added to the sampling program in the West Indian Province segment of the continuing EMAP-Estuaries Program. The first and only sampling to date was in 9/95 at six stations, most of which were in the South Bay; only one station was in North Bay. Sampling includes measurements of water quality, sediment chemistry, sediment toxicity; chlorophyll and eutrophication; tissue residual analysis; biomarkers of fish health condition; indicators of ecological health such as benthic and fish populations; presence of submerged aquatic vegetation. (Haddad et al. 1995; Johnson Controls 1995; J. Macauley, EPA, pers. comm.)

NOAA

NOAA Status & Trends Program. This program assesses current status of and changes over time in environmental health of estuarine and coastal waters. Most data are collected through the National Benthic Surveillance Project, which measures organic and inorganic contaminants in sediments and bottom-dwelling fish, and the Mussel Watch Project, which measures contaminants in mussels or oysters. Sampling is done approximately biennially. There are three Mussel Watch sites in Biscayne Bay where oysters are sampled, one at the north end of the bay and two in the southern bay (Goulds Canal and Princeton Canal). Two Benthic Surveillance sites are in Biscayne Bay, one in the north basin and the other at Chicken Key in the central basin; the species monitored is pinfish. 1990 data showed a good correlation between concentrations of PCBs and DDT and population density within 20 km (12.4 mi) of the sampling sites; levels of these contaminants were higher at the north Biscayne Bay site than at others in South Florida. A separate study was begun in 1995 cooperatively with FDEP to determine severity and spatial extent of toxicity in surficial sediments in Biscayne Bay. Fine-grained sediments from deposition zones with water depths of 1.5 m (5 ft) or greater were sampled at about 30 stations. Microtox sediment toxicity tests were conducted by the Charleston Laboratory, copepod sediment toxicity tests by the Univ. of S.C., and porewater toxicity tests on sea urchins by FWS, Corpus Christi, TX. Data are also being collected on several biomarkers of fish and oyster condition and exposure to contaminants in Biscayne Bay. (Cantillo et al. 1993; Haddad et al. 1995; Scott et al. 1994a)

Pesticide monitoring in Florida Bay and agricultural watershed. In 11/93, 34 stations were sampled by the NMFS/SEFSC Charleston Laboratory in a preliminary study to measure pesticide levels in surface waters of Florida Bay and an adjacent inland agricultural watershed of Dade Co. Stations were in the bay, at the land-sea interface, and in the C-111 canal system. Three stations were also sampled for sediment pesticide levels. Quantifiable pesticide concentrations were found at four of six canal stations and one of the bay stations. Endosulfan was the only pesticide measured at concentrations greater than detection limits; levels were well above the Florida water quality criterion. Highest levels were found in the C-111 canal at Highway #9336, near the entrance to ENP. Preliminary screening indicated presence of triazine herbicides at seven stations, but no detectable levels were found. Increased input of agricultural runoff must be considered in plans to increase freshwater flow to the Everglades and Florida Bay. Field monitoring and laboratory toxicity testing will continue during 1995-97 as part of the NOAA

Florida Bay Program to further assess impacts on Florida Bay of contaminants in surface runoff from the agricultural watershed. (Scott et al. 1994b, 1995a,b)

Survey of fish deformities in Biscayne Bay. Between 11/89 and 6/90 about 43,000 fish were caught during normal operation of a small-boat commercial fisherman in north Biscayne Bay and evaluated for abnormalities by the NMFS Miami Laboratory. Stunted or missing dorsal spines or rays, sometimes accompanied by a depression in the dorsal profile, were found in 10 species in 6 families. Scale disorientation was found in six species. Pugheadedness, jaw deformities, and other abnormalities were also observed. The occurrence of similar deformities across several species from the same area suggests an environmental cause. (Browder et al. 1993)

Optical water quality model for Biscayne Bay. The NMFS Beaufort Laboratory, under contract to SFWMD, is developing this model for protection of seagrasses in the bay. Optical water quality was evaluated by examining DERM data from stations in the north, middle, and south basins. Analyses of water color, turbidity, chlorophyll, and light attenuation led to identification of gradients that differentiate the basins. Water quality is much poorer in the north basin than in the middle and south basins; transparency is very good in the southern bay. Chlorophyll declined significantly since the early 1980s, but there is still moderate gradient from north to south. Chlorophyll decrease was not accompanied by declining color, turbidity, or suspended solids. Field surveys were conducted in 4/95 to determine maximum depth distribution of seagrasses in the middle bay and north bay. Estimated light requirements range from 10% for *Halodule wrightii* and *Syringodium filiforme* to 25-30% for *Thalassia testudinum*. Light attenuation is being reexamined at individual water quality stations close to these sampling stations. (Kenworthy and Schwarzschild 1994a,b; 1995a,b)

NPS

Analysis of Mowry Canal water quality and discharge. Water quality and land-use data from county and Federal agencies for the period 1974-81 were analyzed by the ENP South Florida Research Center to assess the impact of discharges into Biscayne Bay. Water quality data from USGS and DERM included physical parameters, nutrients, bacteria, metals, and pesticides. USGS collected data on over 105 parameters in the canal near its mouth from 1975-80. In 1980 and 1981, DERM collected samples for nine parameters from four stations as part of its canal monitoring program. Available data indicate water quality was relatively good. High nitrogen loading (the highest concentrations in the Dade canal system) exists in the area of the north branch of the canal. Agriculture accounts for 52% of land use in the canal basin. Several heavy metals and pesticides (including DDT and its breakdown products, chlordane, dieldrin, and PCBs) were detected in the sediments at the USGS station. (Scheidt and Flora 1983)

USGS/Dade Co. Planning Department

Effects of land use on surface-water quality in the East Everglades. Water quality was evaluated during the 1978 wet season at five developed sites in the East Everglades area because of concern by Dade Co. and ENP about effects of land development in the area. Surface water and soil samples were collected in two agricultural areas, a residential area, a developed site, and a State park unit (now part of ENP) and compared to four undeveloped baseline sites. Data indicate a rock-plowed tomato field was the only site that had a notable effect on water quality, with high concentrations of trace elements and agrichemical residues. Chlorinated hydrocarbon insecticides were detected in soil samples at all test sites except the park area. (Waller 1982)

SFWMD

SWIM Program for Biscayne Bay. The primary goals of the SFWMD Biscayne Bay restoration program, as described in the SWIM Plan, are to improve water quality and restore more natural freshwater flows to the bay. Since 1988, SFWMD has participated in an extensive array of major projects through the SWIM Program, many of these in cooperation with DERM, including science, restoration, and education. The program has expanded the water quality monitoring program for the bay (established by DERM in 1979, see below) and established a long-term database for identification of problems. Ongoing monitoring samples the bay and most primary tributaries monthly. Of 150 statistically significant trends, preliminary data show improvement in 78%. Turbidity, DO, and coliform bacteria showed most improvement. Ammonia and nitrate/nitrite were notably worse. A project has been

initiated with the UF to develop BMPs for South Dade farms in order to reduce nitrogen loading to the bay. Stations in canals near Black Point (landfill site) and the Miami River show the greatest number of undesirable trends. Sediments in some locations exceed the State recommended levels of mercury, lead, zinc, copper, cadmium, PCBs, and chromium. Stormwater runoff is a major water quality concern; more than 50% of the program funding has been on pollution problems created by urban stormwater systems. (Alleman et al. 1995a,b; Germain 1994; SFWMD 1995)

Dade Co. DERM

Ambient surface water canal monitoring. Quarterly water samples are collected at 50 stations in tributaries and canals in Dade for physical parameters; sediment sampling is done intermittently. The General Canal Program includes 50 stations and was to be revamped in 1994 to coordinate with stormwater utility and bay monitoring. The Intensive Canal Program has collected detailed physical and chemical data on a single canal each year since 1980 to determine if agricultural land use or practices are contributing to the degradation of waters in Dade. Surveys show that surface waters have not been degraded below the limits of Class III standards. Testing is not comprehensive for pesticides. (Ignacio 1994)

Sediment chemistry and toxicity. In additional routine sediment sampling, a major baseline study of sediment toxicity in Dade canals was scheduled to begin in 1995. 90 samples will be collected in canals randomly chosen by an E-MAP program. This will be accomplished in cooperation with FDEP, NBS, and NOAA. The NBS laboratory in Atlanta will do three types of toxicity tests: amphipod survival on solid phase, amphipod survival on porewater, and Microtox on organic extracts. (A. Rodriguez, DERM, pers. comm.)

Fish tissue sampling. To supplement canal monitoring, testing of edible tissue of fishes for mercury and other heavy metals was initiated in 1993 in cooperation with FGFWFC. Elevated levels of metals have been found in largemouth bass, redear sunfish and Florida gar from the western section of the Snake Creek Canal in north Dade. In three bass from the Biscayne Canal, mercury levels were high enough to advise limited consumption. Florida gar had levels prohibitively high for food consumption. (Dade DERM 1994d)

Fish kill analysis. A procedure to study causes of fill kills county wide is being implemented. MICROTOX will be used to analyze water samples collected in the immediate area of a kill. (R. Rodriguez, DERM, pers. comm.)

Biscayne Bay Restoration and Enhancement Program. Initiated in 1979 to maintain and improve the value of the Bay system, the program's initial focus was monitoring of the bay and its tributaries and habitat, along with public access improvement. Routine water quality monitoring began in 1979 to identify average conditions, large-scale patterns, and changes over time. Basic parameters were measured monthly or bimonthly at about 40 stations, including several near the mouth of the Miami River. In 1984, emphasis on the Miami River increased and six stations were added in the main river channel. In 1987, in connection with the SWIM Program, another nine stations were added upstream of the salinity control structures and in Tamiami Canal and Wagner Creek. In 1988, the first stormwater outfall improvement project was completed in connection with the program. (Dade DERM 1993b)

Biscayne Bay Routine Surface Water Quality Monitoring Program. Objectives of BBSWQMP are maintenance and improvement of water quality. It has monitored surface water in Dumfoundling Bay, Biscayne Bay, and Card Sound monthly since 1979. Sampling was initiated in the Miami River in 1984 and in most other tributaries in 1988. Stations in Barnes Sound were added in 1989. BBSWQMP conducts long-term routine systematic sampling at established stations, augmented with short-term investigative studies of pollution incidents or specific projects that may contribute to reduced water quality. Scope has expanded from monitoring 15 parameters at 48 stations in 1979 to 20 parameters at 90 stations in 1991. Studies include: sediment testing at marinas, canals, port, and Miami River; mussel tissue analyses for bioaccumulation; Microtox toxicity testing of surface waters; sediment toxicity tests. Water quality in North Bay is generally inferior to Central and South Bay due to impact of canal and river discharges, habitat destruction, development of surrounding uplands, and less tidal exchange. Water quality did not change markedly from 1987-91, but data show an overall average 24% decrease in water clarity in the bay. (Alleman 1991; Dade DERM undated(a),(h); Germain 1994; Haddad et al. 1995)

Pesticide monitoring. Sampling by DERM in 1981-90 detected pesticides in Dade canals, creeks and Biscayne Bay that included endosulfan; heptachlor; P,P'-DDD; P,P'-DDE; P,P'-DDT; perthane; trifluralin; alpha-BHC; 2,3-D; aldrin; dieldrin; and endrin. (Shahane 1994)

Biomonitoring at Black Point. Biomonitoring and sediment quality sampling at Black Point and Black Creek to determine the toxicity of the water in relation to a nearby landfill were conducted until 3/94. (Ignacio 1994)

Miami River Water Quality Plan. An evaluation of available data and topics of concern was done for the Miami River Water Quality Commission. A variety of sediment quality studies have been conducted since the early 1980s. The FDNR, FDER, COE, and DERM found contamination with a variety of hydrocarbons, pesticides, herbicides, trace metals, and polychlorinated biphenyls, in some cases greater than levels reported for other urban U.S. ports. A threat to nontarget marine organisms is the presence of tributyltin, a toxic organotin compound used in antifouling paints. All stations sampled in the Miami River in 1990 and 1992 exceeded the Federal advisory limit, especially in the upstream half of the river, where concentrations reached about seven times the limit. In 1988, the first stormwater outfall improvement project was completed. The City of Miami has continued stormwater drainage retrofitting projects, utilizing matching local and SWIM program funds. DERM has documented that stormwater drainage in the watershed is contaminated by numerous point and nonpoint sources of pollutants. (Dade DERM 1993b)

UM

Study of biota deformities as related to historical sediment contaminants in Biscayne Bay. Surveys were conducted from 2/91 - 9/92 in north and south Biscayne Bay to assess the nature and frequency of deformities and diseases in fish and blue crabs. Most frequent external abnormalities included scale disorientation, missing or deformed fin ray or rays, and disruption of lateral line. Also observed were missing fins, fin erosion, concavity in the dorsal profile, subcutaneous hemorrhages, and ulcers. Most abnormalities were in bony structures. Results showed more abnormalities in the north bay, specifically clusterings of cases at two marinas. Prevalence of abnormalities for all fish surveyed was correlated with concentration of total and aromatic hydrocarbons in sediment samples within 2 km of survey sites. No correlations were found between contaminant concentrations and distribution of abnormalities in individual fish species or crab except between sediment copper levels and abnormalities in blue striped grunt. More recent data on distribution and type of contaminants are needed to implicate or eliminate pollution as a cause of deformities. (Schmale 1994; Gassman et al. 1994)

UF

Use of biocontrol agents. Experimental introduction of a South American parasitic fly was carried out on a Dade Co. golf course to investigate its impact on the mole cricket population. In March 1990, a population of the fly was established by placing a box of 220 puparia in sand on the course. Trapping for flies at monthly intervals suggested an increasing population of the fly. Reduced turf damage by mole crickets in 1991 compared to 1990, as reported by course managers, may or may not have been due to presence of the fly. Use of such biocontrol agents instead of chemical pesticides could reduce input of chemicals to the environment and also result in economic savings. (Frank 1994c)

South Florida Environmental Research Foundation

Limnological survey of Dade Co. lakes. A physical-chemical survey of 124 rockpit lakes was conducted in 1969; 72 of these were resampled in 1976. The goal was to provide baseline data for future studies on changes in water quality in the lakes. Data from both years were analyzed by a multidimensional hyperspace distance program, which clustered the lakes into groups and identified certain lakes as being representative. (Pope and Schroeder 1979; Schroeder and Pope 1979)

Subregion

USGS

Water resources data collection. During each water year (October-September), USGS obtains data on Florida water resources, including stage, discharge, groundwater levels, and water quality of streams, lakes and groundwater wells. In Subregion 9, data are collected from 19 surface water (canal) stations, in cooperation with many municipal, county, state, and other Federal agencies. Since 1974, the Miami Canal station has been one of 22 Florida stations in the National Stream Quality Accounting Network to describe variability in quality of U.S. rivers, detect changes or trends in water quality characteristics, relate trends to upstream land and water use, account for constituent transport between river basins and into estuaries, and provide a consistent database for water quality assessment and hydrologic research. (Comm. Rev. NAWQA 1990; Haire and Price 1993)

National Water-Quality Assessment Program. NAWQA began in 1986 as a pilot program to describe status and trends in quality of a large, representative part of U.S. surface and groundwater resources. It is now a full-scale program that allows information integration at different spatial scales. 60 study units include parts of most major river basins and aquifer systems. The first national topics will focus on pesticides and on nutrients and sediments. Each study unit will have a local liaison committee. South Florida is one of the study units. The Atlantic Coastal Ridge will be part of the study because of the vulnerability of its groundwater. (Comm. Rev. NAWQA 1990; Leahy and Wilber 1991; McPherson 1994)

NPS

Pesticides threat to Everglades National Park. Recognizing the potential threat the widespread use of pesticides in South Florida presented to ENP, a study was conducted to document pesticide use in areas surrounding ENP and assess toxicity to wildlife of identified pesticides. Documentation of use in Dade Co., Collier Co., and the EAA was difficult because reporting of agricultural pesticide use is not required unless the material is a restricted use compound. It was found that 88 pesticides were being used in the area. Also, present programs were inadequate for assessing contamination of groundwater, surface water, or wildlife. (Scheidt 1989)

FDACS

Monitoring of Florida surface waters for pesticides. A state-wide program was recently started to monitor surface water and sediments for pesticides. To assess the extent of pesticide contamination, an inventory of pesticide detections was initiated in 3/93, with information requested from 35 state, regional, and local agencies. 20 agencies responded; 12 provided requested data, among them SFWMD, Dade, and Palm Beach Co. FDEP monitoring in 1991-93 included Broward. The SFWMD data set, primarily samples at water control structures, was the most extensive for both surface water and sediment. Results of the inventory may help indicate water bodies affected by agricultural activities and allow actions to minimize adverse effects. (Shahane 1994)

SFWMD

Surface water quality monitoring network. This program began in the LEC in 1979 and measures physical parameters and nutrients monthly, major ions quarterly, and trace metals biannually. In 1984, bimonthly pesticide monitoring was added. (SFWMD 1994a)

Pesticide residue sampling. During 1976-80, water and/or sediment at various locations in the SFWMD region were sampled in cooperation with USGS. In Palm Beach Co., the Hillsboro Canal was a periodic sampling site. Stations were in an agricultural area and showed high concentrations of DDT, DDE, DDD, chlordane, and dieldrin. The North New River in Broward and the Miami Canal in Dade were also sampled. The highest value of PCBs was found in sediments from the Miami Canal in Hialeah. (Pfeuffer 1985)

AIR QUALITY

Subregion

EPA

Mercury monitoring pilot study. A multiagency 30-day pilot study was conducted in summer 1995 to determine feasibility of modeling atmospheric contribution of mercury to the Everglades. This pilot was limited to three sources in Dade (municipal waste incinerator, a medical waste incinerator, and a Portland cement operation). Ambient samples collected downwind of the Broward incinerator and Port Everglades power plant were to be used to infer source contributions. The study was expected to verify emission data from these sources. 10 receptor sites between urban sources and the Everglades were monitored (8 sites in urban Dade and Broward, 2 sites offshore of BNP). Results will allow evaluation of the utility of source-receptor models to apportion atmospheric mercury to local sources for which emission data exist. It will also provide preliminary data on ratio of anthropogenic sources to background (global) sources. From the preliminary experiments, the utility of air quality and source characterization studies combined with source-receptor modeling can be assessed in calculating atmospheric contribution of mercury to the Everglades. (EPA 1995)

FDEP

Ambient air monitoring network. The air quality monitoring program of the Div. of Air Resources Management collects data from established monitoring sites throughout Florida for the six criteria pollutants (carbon monoxide, lead, nitrogen dioxide, ozone, sulfur dioxide, and particulate matter) plus wind direction and speed. The monitoring network is operated by local agencies. In Subregion 9, air monitoring is conducted by Broward DNRP, Dade DERM, Palm Beach Health Unit, and several private utility companies. There are 11 stations in Palm Beach, 17 in Broward, and 13 in Dade. (FDEP 1992; Haddad et al. 1995)

HABITAT/NATURAL AREA RESTORATION/MITIGATION

Palm Beach County

FGFWFC

Inventory of scrub habitat. An inventory of the Treasure Coast Region included Palm Beach Co. Distribution and condition of scrub habitat were determined by interpretation of published soil surveys, literature review, and infrared photographs and subsequent ground truthing. Recommendations were made on sites to be preserved. The inventory resides in a computerized database and map system. (Fernald 1989)

FDOT

Pond Apple Slough mitigation. The restoration of Pond Apple Slough is a FDOT, District 4, mitigation project. (L. Burnett, FDOT, pers. comm.)

Florida Greenways Program

Local greenways projects. Several municipalities in Palm Beach Co., including Highland Beach, Lake Park, Palm Beach, Palm Beach Gardens, and West Palm Beach (see below) have existing or proposed projects. These incorporate such habitats as utility and transportation corridors, canal and lake shorelines, wetlands, grasslands, and upland forests. Although usually not unaltered natural habitat, the sites serve as buffers that protect open space and water resources. (Fl. Greenways Comm. 1994)

SFWMD

Effectiveness of constructed shoreline to develop littoral habitat. The natural revegetation and benthic production of an open shelf and a bermed shelf constructed in Canal 51 were compared at 3-month intervals between 9/86 and 6/88. The study was in response to a condition for a permit for maintenance dredging of the canal. Results showed bermed shelves were undesirable due to erosion and entrapment of debris and floating vegetation. *Eichhornia* rapidly colonized the open shelf, and as it increased total benthic organisms decreased. This would be the dominant species in littoral shelf habitat if herbicidal control is eliminated. (Rutchey 1992)

Palm Beach Co. DERM

Environmentally Sensitive Lands Acquisition Program. A program to purchase, preserve, and maintain ESLs was initiated in 1991 when voters approved a bond issue for $100 million. An inventory conducted of remaining native ecosystems in the county identified 38 quality sites that were subsequently proposed for acquisition by a citizens advisory committee. Of these, 14 sites totalling more than 22,400 acres are identified as highest priority. Eight of these 14 sites occur in the central and southern portions of the county contained in Subregion 9. Royal Palm Beach Pines, 736 acres with about 44% wetlands, is one of the best remaining examples of the pine flatwoods/wet prairie association in central Palm Beach Co. The 54-acre Seacrest Scrub in Boynton Beach is the largest remaining scrub site in central Palm Beach Co. The 13-acre Rosemary Scrub, also in Boynton Beach, supports 13 rare plant species. Acquisition of the fourth site, the Water Catchment Buffer, is handled by the City of West Palm Beach (see below). Delray Oaks, a 22-acre site in Delray Beach, contains a high-quality mature live oak hammock and small wetland. Knob Hill, a 52-acre site in Boca Raton, is a combination of Florida scrub and oak hammock that provides excellent wildlife habitat. The site includes some of the oldest sand pine trees in the county and its largest concentration of scrub palmetto, as well as a viable population of gopher tortoises. The Yamato Scrub, about 250 acres in Boca Raton, is one of the most diverse Florida scrub plant communities in the region. It includes oak hammocks, scrubby flatwoods, dry prairies, and freshwater wetlands, which harbor five Federally protected plant species and another five that are candidates for listing. The three portions of the Pope John Paul II/IBM/Potomac Scrub comprise 332 acres of high-quality Florida scrub and pine flatwoods. (K. Brennan, Palm Beach DERM, pers. comm.; Culliton and D. Lott 1995; S. Farnsworth, Palm Beach DERM, pers. comm.; Palm Beach DERM 1991; Palm Beach DERM undated; TNC 1994)

Nearshore reef mapping. A project completed in May 1994 mapped all hardbottom within about 914 m (3000 ft) of shore. Areas of special consideration, such as beach restoration projects, are continuing to be mapped. (Haddad et al. 1995)

Environmental enhancement. A resource inventory was conducted during 1990-92 of impacted and natural areas of the AIW in Palm Beach Co. A database contains information on bathymetry, shoreline characteristics, submerged resources (seagrass, coral, sponge, oysters), manatee habitat and location data, marina and dock locations, habitat project areas, and artificial reef projects. The information is used to evaluate potential habitat restoration and enhancement. (Haddad et al. 1995)

City of West Palm Beach

Environmentally Sensitive Lands Program. The Water Catchment Buffer site is 579 acres of wet prairie, marsh, swamp, and hammocks southwest of the City and adjacent to the West Palm Beach Water Catchment Area. Federally endangered snail kites nest and feed in the tract. This ESL site is threatened by road extension and widening. Its acquisition as a preserve is being pursued by the City. The site is considered a greenway for the protection of open space and water resources. (S. Farnsworth, Palm Beach DERM, pers. comm.; Fl. Greenways Comm. 1994; Palm Beach DERM undated)

City of Boca Raton

Environmentally Sensitive Lands Program. The City passed a $12 million bond issue in 1991 to preserve ESLs that would improve surface water and air quality, recharge aquifers, provide habit for plants and wildlife, and provide wildlife corridors. A citizen task force recommended 10 sites for acquisition. The sites have varied habitat, including wetland, red maple forest, cypress swamp, hardwood swamp, live oak hammock, cabbage palm/oak hammock, dry prairie, palmetto prairie, Florida scrub, sand pine scrub, scrubby flatwoods, and pine flatwoods. Some parcels are also in the county's program. The 31-acre Weissman site contains a portion of the historic Hillsborough slough, a shallow freshwater river that ran to the ocean. One site has already been lost to multifamily residential development. (City of Boca Raton 1991)

FAU

Scrub ecosystem research. Vegetation was studied at 13 remnant scrub tracts in Boca Raton for periods ranging from 1-15 years to determine its relation to ridge patterns. Sites with the highest elevations had the greatest species richness. Data analysis revealed a surprising diversity, with more total species and a greater mean number of species per site than the more publicized Central Ridge. Also, a recovery study was being conducted in a scrub area on the FAU campus, where a decade of mowing was discontinued in 1973. Frequent mowing caused species richness to drop about 50%, and may have the same effect as fires. (Austin et al. 1987)

Broward County

EPA/COE/Broward Co. DNRP

West Broward Co. Wetlands Advance Identification Project. The purpose of a project under the EPA ADID program is to facilitate Section 404 permitting by identifying, in advance of any permit application, those sites for which discharge of dredged or fill material would not likely comply with Section 404(b)(1) Guidelines. In 1991, an ADID study identified sensitive wetlands in a 30,000-acre area west of I-75 subject to intense development pressure, drainage, and habitat alteration. 20% of the wetlands were designated unsuitable for fill; 27% were designated for case-by-case review; 53% were designated "suitable with appropriate mitigation." Field work and draft technical document are complete. Negotiations with COE and Broward DNRP regarding appropriate mitigation are ongoing. (EPA 1992, 1994a; Haddad et al. 1995)

USDA

Broward Co. coastal revegetation plan. The NRCS was funded by the Florida Coastal Management Program to develop this plan, which categorizes and classifies present conditions of the Broward coastline and proposes actions for improvement. Revegetation to control erosion, using sea oats, composted yard waste, municipal sludge, and wood chips, was demonstrated at sites in the cities of Hollywood, Fort Lauderdale, and Dania. Sand grain size on beaches from Pompano Beach south to Hallandale was also studied in relation to revegetation. (FCMP 1995; R. Setti, USDA, pers. comm.)

FDOT/City of Dania

Saw palmetto transplant project. FDOT, District 4, tested a new transplant technique for saw palmetto in an experimental planting of 74 plants in a median strip in Griffin Road. All are surviving. They have also been planted at the loop of Dania Beach Blvd. and A1A. FDOT had not previously been able to grow palmetto transplants in South Florida. Saw palmettos will be planted near Fort Lauderdale-Hollywood International Airport and along other roadways during the next 3 years. This is a hardy and low-maintenance native that does not need irrigation or pesticides and will protect from erosion areas that are now barren, such as steep roadside embankments and overpasses. (C. Higgins, FDOT, pers. comm.; Kollin 1994)

Florida Greenways Program

Local greenways projects. Several municipalities in Broward Co., including Davie, Plantation, Sea Ranch Lakes, Tamarac, Pembroke Park, and Wilton Manors, have existing projects in addition to the Broward Urban Greenways project (see below). These incorporate such habitats as utility and transportation corridors, canal and lake shorelines, wetlands, grasslands, and upland forests. Although usually not unaltered natural habitat, the sites serve as buffers that protect open space and water resources and several have habitat restoration as an objective. (Fl. Greenways Comm. 1994)

Broward Co. Community Services Department

Environmentally Sensitive Lands Acquisition Program. A program to purchase, maintain, and enhance sensitive lands, run by Broward Parks and Recreation Div., was initiated in 1989 when voters approved a bond issue for about $75 million. Site resources, including natural and historic characteristics, are inventoried. Extent of invasion by exotic plants and animals is evaluated and remediated. Management strategies are developed for physical protection, restoration, enhancement, and revegetation to maintain natural ecosystem function. As of 6/94, 18 sites were acquired. Habitats include pine flatwoods, cypress/slash pine, cypress wetland, maple/cypress, scrubby flatwoods, sand pine scrub, low and high hammock, pond-apple wetland, saltmarsh/mangroves, and sawgrass prairie. The sawgrass prairie tract was recently purchased as an Everglades buffer strip with SFWMD and other State funds. The Flamingo Road site, with 155 acres of high hammock, is the largest ESL and occupies the western portion of the Long Key ridge, formerly an island in the Everglades. Pine Island Ridge, 101 acres of high hammock with some remnant slash pines, is the next largest site and the highest elevation in Broward. The 97-acre Miramar Pineland contains what may be the oldest and largest slash pines in Broward. Other sites are under 40 acres. One of the smallest, 11-acre Coconut Creek Maple Swamp, contains prime examples of bald cypress, red maple, and pond-apple trees. This hardwood swamp forest has remained healthy because farmers pump excess water into it. The 24-acre Crystal Lake site is an outstanding example of the very rare sand pine scrub community. The 20-acre Military Trail site is the only scrub site in Broward. ownership that protects a complex of high scrub, scrubby flatwoods, and remnant cypress. The site is a relocation site for the gopher tortoise. (Broward PRD undated(a) (b), 1993; G. MacAdam, Broward PRD, pers. comm.)

West Lake Mitigation Program. West Lake, a 1400-acre coastal wetland and mangrove preserve that extends for 5 km (3 mi) along the AIW in Hollywood, is one of the largest mitigation projects ever conducted in Florida. Although surrounded by dense residential and industrial development, including a major port, airport, and highways, West Lake is the best example of mangrove community remaining in Broward and the largest of its kind between West Palm Beach and Miami. Its purchase in 1985 was the result of an 11-year effort led by the Broward Co. Commission, City of Hollywood officials, community leaders, and environmental groups. The purchase

agreement included almost 200 acres of wetland creation. About 123 species of birds have been observed, including 20 considered endangered, threatened, or rare in Florida. West Lake is an important nursery area for fish, especially for the snook, a State species of special concern. This preserve is one of six sites being evaluated by the Florida Greenways Commission regarding critical aspects of creating successful local greenways. Part of the proposed Broward Urban Rivers Greenway, it is operated as a county park and maintained in cooperation with the City of Hollywood (Broward PRD 1989; Fl. Greenways Comm. 1994; G. MacAdam, Broward PRD, pers. comm.; MacAdam 1990).

Tree Tops Marsh Restoration Project. A 24-acre project in Tree Tops Park completed in 1991 includes a 4-acre lake, 11-acre marsh, 3 acres of hammock islands, and 6 acres of transitional zone. It was funded by the Broward Office of Integrated Solid Waste Management to mitigate the impacts to wetlands during construction of an incinerator. Goals were to restore the predrainage condition of the lowland, enhance wildlife and fisheries habitat and diversity, in addition to providing educational and recreational opportunities. (Broward PRD 1992d)

Urban Wilderness Inventory. An Urban Wilderness Advisory Board maintains an inventory of existing natural areas and makes recommendations to the County on acquisition and regulation. Preservation of environmentally sensitive areas is accomplished through designation as Urban Wilderness Areas; these form the Urban Wilderness Park System. Several Environmentally Sensitive Land sites are proposed for this system. One urban wilderness area is Fern Forest Nature Center, 254 acres with 10 plant communities and remnants of the historic Cypress Creek floodway. Deerfield Island, at the mouth of the Hillsboro Canal, is maintained as a FGFWFC Critical Wildlife Area for the gopher tortoise. Among several others are Tivoli Sand Pine Preserve, 23 acres comprising one of the largest remaining stands of sand pine in the county, and Secret Woods, along the New River with cypress-maple, pond apple-mangrove, and laurel oak hammock communities. (Broward Bd. Commiss. 1993b; Broward PRD undated(a), 1992a,b,c; FGFWFC 1994)

Port Everglades Authority

Habitat evaluation and mitigation of mangrove dredging. The 1993 completion of a new container complex at Port Everglades was preceded by more than a decade of controversy over dredging of a natural stand of red mangrove necessary to construct a turning notch. Biologists began a survey of the 70-acre mangrove tract in 1982. Evaluated were vegetation zones, floristics, and fauna including fish, macroinvertebrates, and birds. Productivity was measured by carbon outflow in one tidal cycle. The stand was termed a fringe mangrove area with greatly declining productivity and poor succession. An extensive plan was developed to mitigate dredging of 18 of the 70 acres of mangroves and installation of 900 ft of bulkhead. In 1989, the Port began planting mangrove seedlings on a 23-acre upland site at John U. Lloyd SRA, from which exotic species were removed and the site scraped to form a wetland. Also included were culverts and upland berms to improve tidal flushing in existing mangroves and placement of riprap to protect seedlings and larval fish. To date, this appears successful. In addition, the Port granted a conservation easement to the State for the remaining 52 acres of mangrove adjacent to the Port. (Fisk 1995)

1000 Friends of Florida/The Conservation Fund

Broward Co. Urban River Greenway. This network will provide open space linkages between communities in an intensely urbanized region through use of predominantly man-made waterways. It will focus on the central and south portions of county, specifically the New River, the SFWMD canal system, and the AIW in the vicinity of Port Everglades. Lead partners will be Broward Co., SFWMD, cities of Fort Lauderdale and Dania, Marine Industry Assoc., FAU, and FIU. Implementation will be during the next 3-5 years. (Fl. Greenways Comm. 1994; FOF 1995a; FOF/The Conserv. Fund undated)

Blueways Project. This is a joint private/public effort to develop an aquatic version of the greenways project to maintain open space, create habitat linkages, and develop recreational opportunities. The New River is considered a good candidate because of its natural, geographical, and social characteristics. Initial stages have included meetings to organize a committee to develop a Blueways plan, find funding support, and develop public interest. (Broward DNRP 1993)

FAU

Scrub ecosystem research. A study of scrub sites included a site at Broward Executive Airport. (Austin et al. 1987)

UF

Graphical models for wetland conservation. Simple graphical models, in contrast to GIS technology, were used to compile and display geographic information for environmental planning. Wetland planning in Broward was used as an example application. (Focus and Mazzotti 1995)

Dade County

FAA

Wetlands re-creation at H/DME site. A 1.5-acre site at the NOAA Atlantic Oceanographic and Meteorological Laboratory on Virginia Key is being returned to a wetland by clearing exotic species and lowering existing grades. Implemented by DERM, the site has been excavated and planted with native wetland vegetation as mitigation for an antenna erected by the FAA on the grounds. The wetland vegetation is fully established as of 9/95, and maintenance to control exotic vegetation is ongoing. (FAA 1994; C. Grossenbacher, DERM, pers. comm.)

FGFWFC

Virginia Key Critical Wildlife Area. 400 acres of shallow tidal flats and mangrove forests on the west side of the island were designated as a Critical Wildlife Area, with the cooperation of the City of Miami, Tropical Audubon Society, The Sierra Club Miami Group, and other conservationists. The area was established mainly for more than 25 species of birds that spend the winter resting and feeding in this critical habitat. The area is closed to entry from 8/1 - 5/1 each year. The submerged land portion is encompassed in the "No Entry" zone recently established for manatee protection on the northwest side of Virginia Key. (Dade DERM 1994a; FGFWFC undated)

FDOT

Gratigny Expressway Wetlands project. With assistance from a native plant grower and an ecological restoration consulting firm, FDOT, District 6, converted a high-maintenance grass interchange with drainage ditches, embankments, bridges, roads, and one royal palm into a 6.5-acre wetland with 15 acres of associated upland. Substantial regrading of soil elevations was necessary to achieve suitable wetland conditions and pollution retardation. This effort received the top landscape award for 1994 from the Florida Native Plant Society. (FDOT 1990; FNPS 1994)

Mangrove planting in Oleta River SRA. FDOT, District 6, provides funding for plantings as part of mitigation efforts. (C. Pritchard, FDOT, pers. comm.)

FDEP

Restoration of Bill Baggs Cape Florida SRA. The Div. of Recreation and Parks initiated this massive restoration after Hurricane Andrew. Prior to the storm, only 27 acres of natural plant communities occurred among the 400 acres of uplands. The rest were either developed or covered with fill and infested with Australian pines and 29 other invasive exotic plants. In 8/92 Hurricane Andrew leveled most of the pines and left the park virtually inaccessible and treeless. Although eradication of exotics had been a goal of managers, the scale of this sudden destruction of such extensive infestation had not been encountered. Recommended immediate actions included exotic plant control to prevent germination and resprouting of persistent exotics, constructing a nursery facility to propagate existing native plants, and developing an ecological restoration plan. The plan includes studies of soil chemistry, hydrology, and salinity; quantitative vegetation analyses of comparable pristine areas; and experimental planting plots to determine effects of mulch, watering, etc. Remnant natural maritime hammock, coastal strand, and beach

dune communities are protected from disturbance to allow natural restorative processes to occur. An estimated 1-2 million native plants are being acquired, planted, and maintained. Native communities, including marshes and mangroves, that existed prior to 1926 will be re-established. An example is the replanting of failed sections of the seawall with mangroves being done by Dade DERM. (FDEP 1993; Huck 1993; Schroeder 1994)

FDOF

Pest insect monitoring. The FDOF compiled insect trapping data to provide recommendations on timing of replanting or reseeding pinelands damaged by Hurricane Andrew. It was estimated populations of pest insects would be at background levels by summer 1995 and risk to pine seedlings would be reduced. (Maguire 1995)

SFWMD

SWIM Program for Biscayne Bay. Many habitat restoration efforts by Dade Co. and local municipalities have been supported by SWIM funds, including mangrove, freshwater wetland, and spoil island projects (see Dade DERM below). Proposed restoration projects include an historical landscape analysis of the C-111 basin to quantify relationship between vegetation and hydrologic conditions to explain past and future effects of water management; posting of shoal warning signs to better mark shallow areas to prevent seagrass and hardbottom community damage; and restoration of the Bulk Carrier Site wetland in South Dade. Based on recommendations from Dade Co., NPS, FWS, other agencies and local governments, SFWMD determined high priority areas for preservation: the 14 mangrove areas in Biscayne Bay identified in the Dade Comprehensive Plan coastal element; upland areas necessary to protect BNP from effects of groundwater seepage and runoff; and areas identified in the Southwest Biscayne Bay ADID study. (Alleman et al. 1995a,b)

Land-use mapping. A mapping project related land-use planning to native vegetation distribution. (T. Singleton, SFWMD, pers. comm.)

Dade Co. DERM

Natural Forest Community Inventory. Started in 1990, this project was interrupted by Hurricane Andrew. The inventory provided baseline information about distribution of Dade forests, especially pinelands, prior to the storm. A database contains frequency data for about 35 indicator plant species. A follow-up survey was done after the storm at 18 sites, including county and private lands. (Maguire 1995; J. Maguire, Dade DERM, pers. comm.)

Pine Rockland Inventory. A GIS-based natural area inventory system will be on line by September 1995. The goal is to classify important pine rockland stand conditions in order to identify restoration needs and priorities. Data from 150 stands will be included. Funds were provided in 1994 by the Hurricane Andrew Urban Reforestation Grant Program. (Maguire 1995)

Pine rockland restoration plan following Hurricane Andrew. Monitoring and research priorities were the severe reduction of mature slash pine canopy in central and southern Dade, delayed mortality from physical tree damage and infestations of bark beetles and weevils, invasion of introduced plant species, pine life history and reproductive cycle information, need for restoration and maintenance of fire, and protected species. The first goal is to restore and maintain environmentally endangered pine rocklands to preserve their natural resource values, with objectives to a) re-establish South Florida slash pine in pine rockland habitats affected by Hurricane Andrew, b) restore and maintain naturally occurring plant and animal associations of the habitat, and c) ensure the viability of rare, threatened, endangered, endemic species and species of special concern. The second goal is to achieve a pine rockland forest canopy and understory structure to maximize biotic diversity, with the objective to restore and maintain a forest canopy structure of uneven-aged pine trees and an understory with a mosaic of shrub gaps. (Dade DERM 1994b; Dade PRD 1994a; J. Maguire, DERM, pers. comm.)

Richmond Pineland Planning and Management Project. This is the largest remaining tract of pineland outside of ENP, with over 1400 acres in the 4-mi^2 area. Formerly the site of the Richmond Naval Air Station, these pine rockland forests surrounding Metrozoo are the best example of this habitat in Dade and are habitat for three Federally endangered plants. The land is owned by nine Federal and two county agencies and because of this

multiagency ownership, the DERM and FWS determined a comprehensive management plan was necessary. Funded by FWS (under its Tropical Florida Recovery Project for Plants) and the Dade Co. Tree Trust Fund, the plan was to include detailed assessment of exotic pest plant control strategies, status of endangered plant species, and wildfire control and prescribed burning needs. Information would be mapped on GIS and groundtruthed. (Avino 1993; Dade DERM undated(b); J. Maguire, Dade DERM, pers. comm.)

Endangered Pine Rockland Plant Species Recovery Project. This was part of a continuing cooperative agreement with FWS. 1992-93 surveys on five listed plant taxa determined population status and distribution. Herbarium research defined potential range of each taxa. The Dade Co. Natural Forest Community database was used to identify extant sites within the potential range. Ordination analysis provided indications of habitat quality and suitability and helped prioritize sites for field surveys. Locations of sites found to contain listed taxa were digitized into the county's GIS database. 1992-93 biological monitoring on certain taxa included life history observations, growth studies, and effects of burning. (Dade DERM 1993a; J. Maguire, DERM, pers. comm.)

Prescribed Fire Task Force. Formed with Dade DERM, Dade PRD, FDOF, and Metro-Dade Fire Dept. to address urban prescribed burning and implement county-wide wildland fire management program. (Dade DERM 1993a)

Crandon Park natural areas protection and restoration. This park on Key Biscayne consists of 904 acres of uplands and wetlands and 1228 acres of submerged land. Natural areas include sand dune and coastal strand (one of three natural dune/strand systems left in Dade), mangroves salt marsh, submerged land in Biscayne Bay including hard bottom and seagrass flats, and a unique fossilized mangrove reef thought to be the only one of its kind. The relatively intact natural systems are a rarity in the urban landscape of the LEC. In 1976, the north end of the park was designated a National Environmental Study Area by DOI. Recently Dade designated the northern 200 acres as Bear Cut Preserve (see below). The goal of monitoring is to ensure perpetuation of coastal strand and mangrove communities through effective ecological management based on current scientific information. Fairchild Tropical Garden initiated a pilot inventory of exotic and native flora to identify target taxa, gather phenological data, and monitor changes. Long-term monitoring was proposed, including photomonitoring. Major efforts will involve removing exotic vegetation; replanting with native plants, utilizing site-specific germplasm when possible; and scrapedowns of existing Australian pine communities to create proper conditions for mangrove and saltmarsh revegetation. Ecological monitoring includes bird rookeries. (Dade PRD 1991; C. Grossenbacher, DERM, pers. comm.; Makemson et al. 1992)

Crandon Park wetlands re-creation. As one element of the restoration of Bear Cut Preserve at the north end of Crandon Park, Dade Co. is restoring some wetlands and creating others as mitigation for impacts associated with construction of a replacement sewage force main across Biscayne Bay. The wetlands will be restored and created in areas that were filled 40 years ago during construction of the Rickenbacker Causeway and the Crandon Marina boat basin. These areas were covered with Australian pine and other invasive exotics, until they were cleared after Hurricane Andrew. The wetland will consist of mangrove, saltmarsh, tidal creeks and ponds, and freshwater/brackish prairie. Construction commenced in 5/95. Two wells were installed to determine profile of the site's freshwater lens and depth of scraping needed for the brackish/freshwater marsh. The project was designed cooperatively by WASAD and their consultants, Dade PRD, DERM, FIU, and the Audubon Society. (C. Grossenbacher, DERM, pers. comm.; 1993; Stone and Suman 1995)

Evaluation of potential habitat loss due to construction of sewage pipeline. DERM conducted an environmental assessment of the portion of Biscayne Bay to be impacted by construction of the replacement sewage force main across the bay, completed in 1994. Seagrass and coastal mangroves were habitats that could be affected. The habitats were mapped to aid evaluation of alternative pipeline routes. In addition to mitigation activities at Bear Cut Preserve (above), WASAD agreed to replant seagrass over the trench corridor and also in prop scars in the vicinity of Virginia Key. (C. Grossenbacher, DERM, pers. comm.; 1993; Stone and Suman 1995)

Virginia Key restoration/mitigation. Over the last several years, both City of Miami and Dade Co. Seaport Dept. contractors have damaged mangroves on the Key in violation of Dade Co. Code. These mangroves (about 1.6 acres) will be restored. Also, other mangrove and coastal dune areas will be created/restored on the north end of the Key to mitigate this damage and improve habitat value for nesting sea turtles. In addition, State and

Federal funds received by the City to restore hurricane-damaged areas were to be transferred to DERM for coastal hammock and strand enhancement in Virginia Key Beach Park. (C. Grossenbacher, DERM, pers. comm.)

Biscayne Bay Restoration and Enhancement Program. Many habitat restoration projects are included under this program coordinated by DERM. The projects are funded by grants from the Florida Inland Navigation District through cooperative agreements with SFWMD and by the Port of Miami Mitigation Fund. Support is also provided by the Biscayne Bay Trust Fund. Major program components are spoil island restoration, Oleta River SRA restoration, mangrove plantings and shoreline stabilization, artificial reef program, and dredged depressions filling program. (Biscayne Bay Manage. Comm. undated (a),(b); Coastal Technol. Corp. undated; C. Grossenbacher, DERM, pers. comm.; G. Milano, DERM, pers. comm.)

Coastal mitigation projects in South Dade Co. There are two major projects: 1) Owners of the Old Cutler Bay property are mitigating in order to develop their land; their mitigation activities include donation of 78 acres of coastal band mangrove fringe to BNP and restoration of 26.5 acres of coastal wetlands by backfilling the Florida City canal just north of Turkey Point. 2) The seaport is mitigating dredging activities by scraping and restoring mangroves in two areas including removing roads down to the Bay. Also, many acres of artificial reefs are being installed. (C. Grossenbacher, DERM, pers. comm.)

Southwest Biscayne Bay Wetlands Advance Identification Project. Because of increased threat of development in the coastal area of southeast Dade, regulatory agencies agreed that area wetlands should be examined through EPA's ADID process. The purpose of an ADID project is to facilitate Section 404 permitting by identifying, in advance of any permit application, sites for which discharge of dredged or fill material would not likely comply with Section 404(b)(1) Guidelines. The project was carried out by GIS mapping and functional assessment of wetlands. About 62% of the 23,000-acre project area is wetlands with 11 different wetland cover types. The area is uniquely important because it forms a nearly unbroken chain along the coast, interrupted only by occasional development and drainage channels, forming a semi-continuous corridor for wildlife movement. Although greatly affected by the drainage system, these communities show high value for wildlife food and habitat, storm surge protection, aquifer recharge, prevention of saltwater intrusion, dynamic storage, sediment trapping, and erosion control. Even exotics-dominated areas serve as buffers between native areas and development and as corridors between native-dominated areas. Eight Federally protected species have been seen in the area; two others are listed as threatened by the State and six others are listed as State species of special concern. All wetlands dominated by native vegetation (79% of area) were classified "Generally Unsuitable" for disposal of fill. "Evaluation Required on a Site by Site Basis" was assigned to exotics-dominated areas (11% of wetlands), where the functional assessment was mixed but of generally high value. "Potentially Suitable with Appropriate Mitigation" was assigned to 7% of wetlands, those with modest values for wetland functions and where filling and development would not result in significant degradation, providing suitable mitigation would replace their functions. (Burzycki and Drum 1992; EPA 1992, 1994a)

South Dade wetlands vegetation mapping. The portion of Dade south of S.W. 344 St. includes a large expanse of undeveloped wetlands important to the health of Biscayne Bay, Card Sound, Barnes Sound, and Florida Bay. The wetlands are habitat for several endangered species, including Florida panther, Cape Sable sparrow, and American crocodile. Over 47,000 acres of these wetlands (North C-111 and Model Land basins) are top priority for purchase by Dade Co. under the EELAP. An accurate baseline vegetation map in GIS format is one of the studies needed and is particularly important because Hurricane Andrew may have significantly altered the vegetation composition. The effort is to be compatible with similar projects being conducted in ENP, BNP, and BCNP. Utility of remote sensing for detecting encroachment of invasive species will also be studied. The 2-year project will be conducted under contract to SFWMD. (Burzycki 1994a; Dade DERM undated(g))

National Bulk Carrier's site restoration. Dade DERM purchased this 700-acre site in South Dade, east of Homestead Air Force Base, from The Nature Conservancy in 1991 in order to restore and protect its wetland habitat value and functions. Water table drawdown by the canal network has severely impacted native wetland communities, with substantial exotic vegetation invasion. EPA had funded a mapping project that showed viable mangrove and freshwater communities still existed. The land was 52% exotics-dominated wetland, 27% dense scrub mangrove, and 19% white mangrove secondary forest. The project was to proceed with biological and hydrological assessment, evaluation of the feasibility of various restoration techniques, development of detailed restoration plan

specifications, and implementation of the plan. In 8/92 Hurricane Andrew severely damaged vegetation and complicated and delayed progress. It is proposed to leave standing mangroves alone, create a 150-ft-wide open water area with islands of willow, pond apple, and buttonwood, create interconnecting channels and isolated ponds, and control exotics on the rest of the property while it naturally revegetates to a short-hydroperiod wetland. (Burzycki 1994b; Dade DERM undated(f), 1994c)

Dade Co. PRD

Lead recovery at Trail Glades Gun Range. A recovery plan is being developed for lead shot over 600 acres of sawgrass at the western edge of urban area (at Tamiami Trail and Krome Ave.). Groundwater monitoring and soil tests are included. No habitat mitigation is planned because melaleuca is already present west of the area. (R. Line, Dade PRD, pers. comm.)

Mitigation at M.E. Thompson Park. A conservation land bank was set up in this state-owned land in northwest Dade off Krome Ave. (bordered on west by Dade-Broward Levee; in same area as proposed buffer lakes). The land is mitigation for a landfill (Metro-Dade Solid Waste Management) and a developed area north of Kendall Drive. Site was originally homogeneous sawgrass; is now 30% melaleuca that spread from plantings when the site was a campground developed by COE in the 1950s. Melaleuca control is being attempted here because it has not spread far into the conservation area to the west. There is a $1M program to conduct aerial (helicopter) spraying of melaleuca heads with various combinations of herbicides while waiting for development and approval of biological controls. Efforts will also involve mechanical control along with prescribed burning. (Coop. Ext. Serv. undated; R. Line, Dade PRD, pers. comm.; McHargue and Hammer 1994)

Natural areas mapping. GIS- and GPS-based mapping was done for 790 acres of uplands, including Deering Estate, Matheson Hammock, Metrozoo/Larry & Penny Thompson Park, and Tamiami Pineland Preserve, to evaluate the utility of false-color infrared photography to monitor natural areas in Dade Co. The Univ. of Wisconsin Institute for Environmental Studies is supplying computer equipment and software and setting up computerized systems for assembling map layers and analyzing remotely sensed images. This is a joint effort with Fairchild Tropical Garden. (Dade DERM undated(a); Fisher 1994; Maguire 1995)

Post-hurricane natural areas recovery program. At $5.5M for a 3-year program, this was the largest local funding for natural areas restoration in U.S. history. Objectives were to: 1) remove exotic plants in severely threatened areas; 2) coordinate with FDOF to conduct prescribed burns to reduce fuel load and fire threat; and 3) revegetate natural areas destroyed by post-hurricane activities (e.g., dump sites, military staging areas) before exotic plants invade. This will eliminate immediate threats that would otherwise destroy sensitive natural areas. By the end of 3 years, the areas should be able to recover on their own. Program emphasizes recovery of hammocks; at the time of funding, no one considered pinelands seriously threatened. (Dade PRD undated(b); M. Gregg, Dade PRD, pers. comm.)

Post-hurricane pineland restoration program. Initially after Hurricane Andrew in 8/92, the pine rockland forests appeared to survive direct physical damage reasonably well, and efforts focused on the crisis of exotic vines invading the hammocks. However, 8 months later rapid mortality of slash pine began, with unexpected abnormally high toll from pine bark beetles (95-100% vs. expected 50-60%). This 5-year program was funded for $3.5M to try to preserve the pineland ecosystem, and was to cover 37 park sites containing 1,061 acres of pines. (Dade PRD 1994a; M. Gregg, Dade PRD, pers. comm.)

Collection of slash pine seed. In 9/93, a project was started with FDOF to collect viable seeds from remaining living pines. The two agencies collected 24 bushels of cones (about 200,000 seeds) from several parks in Dade. Seeds were stored in north Florida where State foresters are assessing their viability and propagating them for replanting. Seed collection will continue in future years. [Seedlings from these seeds were planted in South Dade in summer 1995.] (McHargue and Hammer 1994)

Hammock restoration program. This program is restoring four of the largest hammocks in Dade (Matheson, Snapper Creek, Deering Estate, and Castellow) following Hurricane Andrew. Goals are to restore native

tree canopy, facilitate native seedling recruitment in the understory, and removing over 50 exotic species. (Flynn 1994; Klein undated; McHargue and 1994)

Management plans for rockland forests. A conservation partnership between Dade PRD, The Nature Conservancy, and Fairchild Tropical Garden led to development of plans for many significant publicly owned rockland forests. (Dade DERM 1993a)

Metro-Dade Co. Planning Department

Wetland basin analyses and management plans. A program was initiated for developing plans for all wetland basins facing development or pressure of agricultural use. Plans will address water retention, drainage, and mitigation for loss of wetlands habitat. The priority area is Bird Drive Everglades basin, 32 km^2 (12½ mi^2) in area, west of Krome Ave. between Tamiami Trail on the north and Kendall Drive on the south. Wildlife and habitat values are being determined in cooperation with COE, FWS, FDER, and SFWMD. Second priority is North Trail basin west of the Turnpike, north of Tamiami Trail and south of 25 St. NW. Third priority is southeast Dade wetlands. (Metro-Dade Plan. Dept. 1989)

Office of County Manager

Environmentally Endangered Lands Acquisition Program. This program was initiated in 1990 when Dade voters approved a 2-year tax to raise $90 million to preserve natural lands. Endangered lands are prioritized by many criteria. By 2/95, 19 sites totaling 428 acres had been purchased. 11 of these are priority sites under the State CARL program. The majority of the land is pineland or a combination pineland and hammock. Sites totaling more than 48,000 acres are on the Priority A List for acquisition. By far the most ambitious project is the South Dade Wetlands Acquisition Project, 47,639 acres of freshwater wetlands that Dade EELAP and SFWMD SOR Program are jointly funding. The southern 3/4 of the Model Land basin is one of the most pristine wetland areas outside of ENP. Sheet flow of freshwater across this area into Biscayne Bay is still intact, making the site extremely important for preservation of the South Florida marine system. Eleven tracts of tropical hammocks, including five CARL sites, totaling 215 acres are also on the Priority A List. Eleven tracts of Miami Rockridge and Tamiami pinelands, including four CARL sites, totaling 312 acres are also proposed. (Burzycki 1994a; Dade DERM undated(g), 1992b, 1993c; C. Grossenbacher, DERM, pers. comm.; Land Trust Dade Co. et al. 1994; Muhs 1994; Young 1994, 1995)

Land Trust of Dade Co./Dade Co. PRD/ Metro-Dade Office of Community Development/Redland Conservancy/Florida Greenways Program

Greenways for Dade. In response to demand for open space and recreational land, Dade Co. began in 1969 a number of land-use studies regarding open space corridors. These continued into the mid-1970s, but resulted in only three small projects totaling 10 km (6 mi) in length. Intensive new efforts got underway in 1993 with planning sessions to guide rebuilding South Dade after Hurricane Andrew. A task force recommended a series of linear corridors and greenways to provide wildlife routes as well as trails for pedestrians, bicycles, etc. to link agricultural communities, parks, natural areas, and public places in the region bounded by Cutler Ridge on the north, Biscayne Bay on the east, and ENP on the west and south. The South Dade Greenway Network would be one link in a county-wide network of open space, wildlife, and human corridors along canals, rivers, utility easements, railroad rights-of-way, Metrorail corridors, beach and bay shoreline, and bicycle and pedestrian paths. Some municipalities including North Miami Beach and Biscayne Park have existing or proposed projects. The Goulds Greenway Trail is proposed for redevelopment of the Goulds neighborhood, emphasizing linear parkland along U.S. 1 and a transit line and anchored by parkland along Black Creek Canal on the north and the proposed Rockridge Pineland Preserve/Parkland on the south. (Alden undated; Land Trust Dade Co. et al. 1994; UM/FIU 1992; Fl. Greenways Comm. 1994; FOF/The Conserv. Fund 1994)

City of Miami

Virginia Key Master Plan. This plan presents an approach to developing the barrier island for recreational uses, while ensuring environmentally sensitive areas (tidal flats, mangrove tidal marshes, beach/dunes, and coastal

hardwood hammocks) remain undisturbed and undeveloped, restored when necessary, and protected from inappropriate public activity. (City of Miami 1987)

Evaluation of Virginia Key habitat. Habitat assessment is taking place in association with plans to redevelop Virginia Key Beach Park as a commercial campground. The area contains diverse natural habitats and rare species, especially plants. A consulting firm was contracted by the City to conduct a biological inventory to evaluate habitat value and development potential of a coastal hammock in the area. (Biolog. Environ. Consult. 1995; Paddon and Suman 1995)

UM

Effects of non-native plant species on regeneration of hammocks following Hurricane Andrew. Research started in fall 1992 in three Dade parks (Matheson, Deering, and Castellow Hammock) and simultaneously in three ENP hammocks. Vegetation in Dade parks contained more than 30% alien species, compared to less than 3% in ENP. Most abundant non-native vines were skunk vine, jasmine, air potato, wood rose, and pothos. Most abundant non-native shrubs and trees were papaya, castor bean, Bishopwood, shoebutton ardisia, surinam cherry, and Brazilian pepper. (Horvitz 1994)

FIU

Hurricane damage assessment in hammocks. In summer 1993, a European architectural methodology was used to assess structural damage to hammocks caused by Hurricane Andrew. Three study hammocks were in the urban area (Matheson, Deering, and Castellow hammocks); the other three were in ENP, BNP, and Key Largo. Each tree was mapped along established transects at different distances from the storm's center to assess how damaged varied. Pre-storm structure of each transect was also determined. (M. Ross, FIU, pers. comm.)

Tropical Audubon Society/Junior League of Miami

Xeriscape landscape restoration. A 3-acre site surrounding TAS headquarters in South Miami were restored after being virtually untended for nearly 40 years. The grounds are on the Miami rockridge and were part of the Dade pine rockland and hardwood hammock forests. Intrusive and poisonous exotics were removed. When the site was cleared of unwanted plants, pine rockland plants dormant for many years started growing. Reforestation used only native species, selected for water conservation. Included are a pineland with young slash pine, saw palmetto, and wildflowers (some endangered); a hammock typical of South Miami; and a second hammock characteristic of the Brickell Hammock. The project is intended to serve as a model for gardeners. (Link and Lippincott undated)

Florida Power & Light Company

South Dade Mitigation Bank. FPL has set aside as a mitigation bank 13,367 acres of land it owns in the Model Land basin of South Dade Co. This land will be used to compensate for wetlands unavoidably lost in construction and maintenance of facilities to provide electrical service. This will allow FPL to concentrate future mitigation into a large contiguous parcel and provide greater assurance of ecological benefits. Restoration actions will include removal of exotic vegetation and replanting with native species, removal of unnatural physical features, hydrological improvements, and protected species enhancement. (Cotleur Hearing 1995)

Subregion

COE/FDEP

Coast of Florida erosion and storm effects study. A regional GIS database initiated in 1989 includes 9 primary coverages and 50 associated coverages for the coastal zone from the south tip of Key Biscayne in Dade north through Broward to the Palm Beach/Martin line. The project is developing a comprehensive body of

knowledge of coastal processes and environmental resources along the Florida Atlantic Coast and will result in enhanced shore protection projects and improved coastal zone management. (Haddad et al. 1995)

FNAI

Assessment of southeast Florida coastal upland natural communities. A 2½-year project identified and assessed the quality of remaining natural upland communities (beach dune, strand, maritime hammock) on barrier islands and ocean shores from Brevard to Dade. Standard minimum parcel size of 20 acres was reduced to 10 acres for this region in order to include the few small natural areas remaining in Palm Beach, Broward, and Dade counties. Sites were identified with aerial photography from FDOT. New field survey data were combined with the existing FNAI database. Communities were ranked by species diversity, structure, degree of disturbance, and degree of exotic invasion. 16 natural areas were found along the coastline between West Palm Beach and Cape Florida (8 in Palm Beach, 5 in Broward, and 3 in Dade). Three sites were classed as excellent examples of the habitat: MacArthur Beach State Park (Palm Beach), Gumbo Limbo Nature Center (Palm Beach), and Bartlett Estate (Broward). Four sites were classed as good: Boynton Beach Park (Palm Beach), Hugh Taylor Birch SRA (Broward), John U. Lloyd SRA (Broward), and North Beach Park/Dania Tract (Broward) for beach dune and coastal strand. (Johnson et al. 1993)

FGFWFC

Population biology of the American crocodile. Almost 400 crocodile hatchlings from nests on Key Largo were tagged during 1978-91. These dispersed throughout adjacent mangrove swamps and also to the mainland as far as 113 km (70 mi). Highway mortality was the greatest source of deaths, especially along U.S. 1. Aspects of population dynamics such as sex ratio, growth, natality, and survival were studied. (Moler et al. 1992)

FDEP

Plan to control exotic pest plants. Input was obtained from each county to establish a state-wide program to control exotics according to ecosystem management principles. A mail survey conducted by Dade PRD gathered information on the statewide status of exotic pest plant invasion into natural areas on public lands, how it impacts local governments, and research and funding needed to control exotics. FDEP surveyed State and Federal governments. Information was to be used to develop funding legislation for exotic pest plant control research, removal, and restoration. (Dade PRD undated(a); Gregg 1994; D. Schmitz, FDEP, pers. comm.)

UF

Wildlife diversity study. FGFWFC is providing funds through the Nongame Wildlife Program for a 5-year study of relationships between human population growth and wildlife species diversity in hardwood hammock fragments. (FGFWFC 1993)

FSU

Encroachment and land-use change in South Florida. Little is known about effectiveness of biosphere preserves, especially when areas surrounding reserves have significant human population growth. Under the U.S. Man and the Biosphere Program, research is being conducted to evaluate sustainability as related to reserves such as the Everglades. GIS analyses were done to produce encroachment maps showing the change in groundcover from natural areas (wetlands, non-wetlands) to human use (e.g., agriculture). Data sources were U.S. census, USGS, and SFWMD. Many areas on the western edge of the LEC urban area showed more intense encroachment than would be expected from census data. (Walker and Solecki 1994)

HDS-GIS data dictionary. A listing, including data descriptions, was compiled of GIS databases available for Everglades Biosphere Reserve and South Florida. (Zapolsky 1993)

University of Georgia

Genetics profile of South Florida slash pine. Spatial separation of the forests plus differing edaphic conditions on which they grow provide concern that genetic differentiation may exist throughout the region. Under contract from Dade DERM, genetic background data was gathered to help determine appropriate slash pine forest sites as seed donor sites for future restoration. DERM coordinated collection of buds or needles with FDOF from 48 trees at each of 8 sites in pine rocklands and 8 sites in sandy pinelands from Lee, Hendry, and Palm Beach counties south to the Lower Keys. Allozyme testing was conducted to determine if there is genetic differentiation between forests growing on oolitic limestone and those in sand, if disjunct forests are reproductively isolated or genetically different, and if the genetic profile of the Miami Rock Ridge sites is different from other rockland sites. Results show there is a large amount of gene exchange between slash pine on rocky and sandy soils. (Dade DERM undated(d), 1994b; Hamrick 1995; Maguire 1995)

BIOTA/PROTECTED SPECIES

Palm Beach County

FWS

Breeding bird survey. This national survey collected information on distributions, local densities, and population trends of breeding birds from 1969-1983. One of the Florida survey routes was in Boca Raton and was covered the entire 15 years. (Cox 1987)

FGFWFC

Southeastern beach mouse survey. Two sites in Palm Beach Co. (MacArthur Beach State Park and Manalapan Beach) were included in a 1988-89 trap survey of the five best examples of remaining each dune habitat from Brevard to Palm Beach Co. No evidence of beach mouse populations was found in Palm Beach Co. It is unlikely the mouse occurs south of St. Lucie Co. At the time of the survey, a private landowner on Manalapan Beach, just north of Boynton Beach, was completing a major dune system restoration, including a low foredune vegetated with sea oats, other native graminoids, and beach shrubs. When established, this habitat could possibly support a beach mouse population. (Robson 1989a)

Palm Beach Co. DERM

Sea turtle survey. An ongoing program coordinates a survey network and estimates nesting densities and success rates. (Haddad et al. 1995)

Town of Palm Beach

Sea turtle monitoring at prefabricated reef. The period 4/19/93 - 10/5/93 was the first season of a 3-year survey of nesting success following installation of an experimental prefabricated erosion prevention concrete and steel reef along 1219 m (4000 ft) of beach at Palm Beach. Nesting of loggerhead turtles was observed from May - August. Green and leatherback turtles are also known to nest on beaches of Palm Beach, but in low numbers. This is the first systematic study of sea turtle nesting in the Town of Palm Beach. (Town of Palm Beach 1993)

City of Boca Raton

Sea turtle nesting survey. Since 1979, the City has conducted surveys for nesting activity at the public beach. (Harris et al. 1984)

Sea Turtle Nest Protection and Relocation Program. Extensive nest relocation was conducted in 1988 because of severe erosion problems, as well as the North Beach Nourishment Project. A study on hatching and emergence success was conducted by Florida Atlantic University at four beach sites in Boca Raton during the 1990 season subsequent to the renourishment project. A 3-year follow-up study on the 1985 South Beach Nourishment Project showed improved nesting densities and success. (Broadwell 1992; Wolf 1989)

FIU

Erosion prevention study. In 1987, a 305-m (1000-ft) line of erosion prevention modules was installed parallel to the beach in front of the Dupont Estate. Monitoring during 1988 and 1989 turtle nesting seasons determined these concrete structures did not interfere with nesting. (Fletemeyer 1991)

FAU

Sea turtle nesting patterns. A 1989-92 survey of nesting patterns of loggerhead turtles on a Boca Raton beach showed nesting density was strongly correlated with elevation of objects (trees, buildings) behind the beach. (Salmon et al. 1994)

Hatchling misorientation. Experiments conducted on a Boca Raton beach showed misorientation caused by anthropogenic light sources was common. The high incidence at Boca Raton was caused by presence of both light sources and background silhouettes (outlines of high buildings) with many light gaps. Masking spaces between buildings with tall trees, dunes, or other barriers would help correct the problem. (Reiners et al. 1994)

Survey of natural resources on FAU campus. An inventory of resources in natural and man-made areas of the campus was conducted so these features might be considered in future campus development projects. Several areas were recommended for preservation as study areas (e.g., as pine woods succession or scrub ridge succession) or protected species refuges. Gopher tortoises were common in protected areas on campus. Burrowing owls had declined to an estimated four active burrows in 1986 from 18 in 1971 when the campus was designated a National Audubon Sanctuary for this species. Projected causes of decline were human encroachment; introduction of trees to the landscape; predation by feral cats, dogs, or giant marine toads; or pesticide poisoning. (Burch and Marsh 1987)

UF

Hatchling misorientation. Experiments conducted on Delray Beach by the Archie Carr Center for Sea Turtle Research showed that not only were artificial lights that could be seen directly from the beach responsible for disorientation but so also were lights that could not be seen directly, such as light reflected from buildings and vegetation or scattered by clouds and mist. (Witherington 1990)

UM

Ecology of coral-octocoral communities. The survey was conducted of the biological community of three parallel submarine terraces, which form a northern reef tract along Florida's Southeast Coast. The principal area investigated was off Boca Raton. (Goldberg 1973)

Broward Co. Audubon Society

Monitoring and sampling of stranded turtles. In 1990, a stranding hotline sponsored by Broward Co. Audubon Society was expanded to Palm Beach Co. Necropsies are conducted and stomach samples collected. Most juvenile green turtles contained a mix of algae and seagrasses representative of offshore flora proximate to stranding locations. Presence of rhodophytic algae and sighting of turtles feeding on these plants show importance of hardbottom areas off Broward and Palm Beach counties. (Wershoven and Wershoven 1992b)

Broward County

Broward Co. DNRP

Sea turtle conservation program. A major conservation effort was started in 1975 and funded since 1978 to mitigate problems threatening sea turtle survival in Broward. Nova Univ. has been contracted since 1981 to conduct daily surveys on Broward beaches during turtle nesting season, normally from mid-April to mid-September. The project includes relocating eggs from nests endangered by natural process or human activities, surveying turtle nesting patterns and effects of beach renourishment, assessing success of recruitment, disposing of turtle carcasses, and educating the public about turtle conservation. Surveys include the entire shoreline of Broward: Hillsboro-Deerfield beach, Pompano beach, Fort Lauderdale beach, John U. Lloyd SRA beach (conducted by park personnel), and Hollywood-Hallandale beach. Since 1975, many research studies have been conducted in concert with the basic nesting survey. These include studies on pen rearing and head starting, tagging, strandings, hatchling incubation success, artificial incubation methods, sex-temperature determination, hatchling light orientation and dispersal, juvenile behavior and dispersal, and analysis of heavy metals and PCBs in eggs. Many cooperators in these studies, besides Nova Univ. and Broward Co., include Oceanworld; Theater of the Sea; FPL; the cities of Fort Lauderdale, Hollywood, and Pompano Beach; and Palm Beach Co. (Burney and Margolis 1993; Burney and Mattison undated, 1993; Burney et al. 1990; Fletemeyer undated, 1983, 1984; Mattison et al. 1990, 1994)

Fort Lauderdale Executive Airport

Protection of burrowing owls. In 1994, there were about 120 burrowing owls nesting on airport property. Concerned that mowing operations might disturb nesting, officials erected 57 T-shaped pipes to mark burrows. The pipes show mowers which areas to avoid and also provide hunting perches for the owls. More perches were planned for the expanding owl population. (Blom 1994)

FAU

Behavior of squirrel monkeys. Behavior of a semi-wild, reproducing colony of the non-native squirrel monkey was studied at Bartlett Estate in Fort Lauderdale. (Wheeler 1990)

UF

Resource utilization by vervet monkeys in mangrove system. Observations of a breeding, free-ranging population of the non-native vervet monkey were made in 1991-92 in West Lake Park to census the population and identify food sources. Results showed extensive use of the three species of mangroves, especially red mangrove. 60% of the parts eaten were budding leaves and/or shoots. Invertebrates comprised 17% of the diet. (Hyler 1995)

Broward Co. Audubon Society

Assessment of juvenile green turtles in Broward Co. Since 1986, assessment of population of juvenile green turtles and its foraging and resting habitat has been conducted in Broward. Presence of substantial numbers of green turtles observed by divers feeding and resting indicated Broward reef areas are important developmental habitat. Juveniles utilize a large expanse of hardbottom reef, which provides adequate forage and hydrographical relief. Potential threats are recreational diving, boating activities, and frequent freshwater discharges from water management canals during heavy rainfall, which may be linked to algae blooms that out-compete preferred algal forage. (Wershoven and Wershoven 1989, 1992a)

Monitoring and sampling of stranded turtles. A stranding hotline sponsored by Broward Co. Audubon Society has gathered reports in Broward since 1986. Necropsies are conducted and stomach samples collected. Most juvenile green turtles contained a mix of algae and seagrasses representative of offshore flora proximate to stranding locations. Presence of rhodophytic algae and sighting of turtles feeding upon these plants show importance of hardbottom areas of Broward. (Wershoven and Wershoven 1992b)

Flamingo Gardens

Wood stork breeding program. A program to try to breed captive wood storks was transferred to the Gardens from the Miami Museum of Science in 1992. No one has ever bred wood storks in captivity. This colony of eight birds (all injured) is the largest in captivity. They are housed in a free-flight aviary in a simulated swamp environment with native plants. The water table will be lowered and fish supply will be increased during breeding season to mimic natural conditions. Video will record the birds' behavior. One egg was laid soon after the birds' arrival at the Gardens but did not survive. One nest was built in 1994, but no eggs were laid. (M. Ruggieri, Senior Keeper, Flamingo Gardens, pers. comm.)

Dade County

COE/SFWMD

Manatee protection at flood control structures. Crushing and/or drowning in flood control gates is a major cause of manatee mortality in central and southern Florida. 42 deaths were documented at seven different structures operated by SFWMD from 1974-1993. Cooperative engineering and environmental studies were conducted to evaluate methods to avert this mortality. Several experimental alterations of structure and operation of the gates have not been completely successful. The present plan is to implement the operational protocol for locks and

spillways in the Manatee Protection Plan for Water Control Structures and install a series of pressure sensitive plungers on the gate bottoms. The plungers transmit a signal used to reverse the gate direction when resistance is encountered; a gate will open when the sensor is activated by an object. (COE 1995a; Dade DERM 1994a)

FWS/UF

Endangered snail rescue effort. A few days after Hurricane Andrew devastated hammock habitat at Monkey Jungle south of Miami on 8/24/92, a cooperative effort was initiated by FWS and UF to rescue snails that had been transplanted to Monkey Jungle. These included many varieties and forms now extinct in the Florida Keys. The snails were now exposed to direct sunlight, and UF made plans to house them until the hammock could recover. (Emmel 1992)

NMFS

Sea turtle nesting survey on Virginia Key. The NMFS Miami Laboratory has conducted nest counts on the beach of Virginia Key since 1990. (W. Teas, NMFS, pers. comm.)

FDEP

Natural landscape of Key Biscayne. A species list was developed for a previously undocumented tropical hardwood hammock discovered in 1992. General patterns of the island's historic native vegetation and flora were also reviewed. (Huck 1995)

Sea turtle nesting survey at Cape Florida. The beaches of Bill Baggs Cape Florida SRA on Key Biscayne have been monitored for turtle nesting since 1980. (Conley and Hoffman 1987; Harris et al. 1984)

Dade Co. DERM

Manatee distribution surveys. Aerial surveys have been conducted since 12/89, either monthly or biweekly year-round. FDNR conducted surveys from 12/87-3/90, usually biweekly. These data plus public sightings are entered into a GIS. (Dade DERM 1994a; K. Mayo, DERM, pers. comm.)

Manatee mortality database. Data on manatee mortality have been recorded since 1974. Carcasses are recovered, necropsies performed, and cause of death determined. (Dade DERM 1994a)

Manatee protection plan. Dade Co. implements this plan to reduce manatee mortalities and injuries, protect manatee habitat, minimize manatee harassment, increase public awareness of the need to protect manatees and their environment, and monitor status of manatee populations and their habitats. (Dade DERM 1994a)

Seagrass habitat monitoring. Monitoring is conducted at 14 stations representative of broad areas of seagrass beds in Biscayne Bay; 11 stations are in the north and middle basins, 3 are in Manatee Bay at the mouth of the C-111 canal. The program began in fall 1985, and a permanent transect was established at each station. Sampling for biotic and abiotic parameters is done quarterly. Species composition, relative abundance, and linear coverage along each transect are measured by direct count in a 1-m2 grid divided into 25 equal subunits. Sediment depth is estimated, and standing crop is estimated by collecting aboveground biomass from quadrats adjacent to the grids. (Fourqurean 1995)

Post-hurricane reef monitoring. In 1992, Hurricane Andrew passed in close proximity to 8 natural reef biological monitoring stations and 11 artificial reef sites in central and northern Dade Co. Qualitative visual surveys and photogrammetric surveys were used to estimate hurricane impact on the natural reefs. The algal and sponge communities sustained the greatest damage. Visual surveys of artificial reefs showed damage ranged from no impact to total structural modification. (Blair et al. 1994)

Dade Co. PRD

Sea turtle nesting survey. Since 1980, Miami area beaches have been surveyed for nesting activity as part of the FDEP index survey. The area monitored extends approximately 23 km (14 mi), from Government Cut at the south tip of Miami Beach north to Golden Beach, almost at the Broward line. Each nest found is relocated to a hatchery. (B. Ahern, PRD, pers. comm.; Harris et al. 1984)

Sea turtle nesting survey at Crandon Park. The beaches of Crandon Park have been patrolled for nests since 1981. Eggs are collected from nests to protect them from beach equipment, poaching, and predators and placed in a hatchery in the park. Hatchlings are released from park beaches. Until 1993, the survey was conducted by TAS. (Dade DERM 1991; Harris et al. 1984)

Barry University

Loggerhead sea turtle emergence. Hatching was observed on Key Biscayne throughout the 1994 nesting season. In addition to temperature cues, emergence appeared to be correlated with social interaction, including the first report of hatchling sea turtle vocalization. (Hibler 1995)

Sea urchin density. Densities of sea urchins and turtle grass were measured during 5/94-2/95 at three sites along Key Biscayne and Virginia Key. The data add to a 7-year database on seagrass ecology near Key Biscayne. (Montague et al. 1995)

UM

Ecological risk assessment and ecosystem management. This project is being done under contract with the COE Waterways Experiment Station to support development of new experimental and modeling capabilities to understand health and management of coastal ecosystems. Tools will be developed to evaluate consequences of alternate water management strategies, including changes in freshwater flow to estuaries, effects of nutrients, and effects on estuaries of freshwater plant control. Several field (Biscayne Bay) and laboratory studies will deal with responses of seagrasses to anthropogenic stress. Another is working to identify indicator species of stress in fish communities. A 13-month field survey was followed with salinity challenge experiments on eight species: five that dominate habitats near canal mouths (silver jenny, pinfish, bluestriped grunt, gulf toadfish, and rainwater killifish) and three that are less common (spotted seatrout, tomtate, and sheepshead minnow). (CMEA 1995; Serafy 1995)

Mangrove biology. Many experimental studies have been done on productivity and decomposition of mangroves in areas of Biscayne Bay and southeast Dade Co. located in Subregion 9. (Bohnsack and Mazzotti 1975; Fell et al. 1975; Fell and Master 1973; Hildebrand 1977; Kimball and Teas 1975; Miller 1972, 1975; Pool et al. 1975; Rielinger 1991; Teas 1974, 1976)

UM/FAU

Post-hurricane nesting survival. Surveys were conducted after Hurricane Andrew in 8/92. Egg mortality due to storm surge was 100% in nests on Key Biscayne and Virginia Key closest to the storm's eye. In areas further away, delayed mortality was caused by changed beach topography. On Fisher Island, just north of Virginia Key, eight nests relocated from Jupiter in a beach renourishment study suffered heavy mortality from a combination of storm surge, later torrential rains, and heavy accumulation of sand. (Leone-Kabler et al. 1994; Milton et al. 1994; Shaw et al. 1994)

UM/FIU/FDEP

Biscayne Bay Red Drum Stock Enhancement Program. Since 1990, feasibility of marine finfish stock enhancement for Biscayne Bay, specifically for red drum, has been investigated through a joint program of FDEP, Dade DERM, UM, and FIU. Red drum was a common native species in the bay until numbers declined rapidly in the 1940s-60s. Adults are spawned and larvae are raised in ponds at a FDEP hatchery. Fingerlings are transferred to grow-out tanks or ponds at UM and FIU. Prior to release fish 3-5" are tagged with binary coded wire tags; those

6" or larger are tagged with internal anchor tags. Over 50,000 red drum fingerlings per year are being tagged and stocked in the bay; in 1994 more than 63,000 were released. Over 150 fish tagged fish have been returned by anglers, and schools of red drum have been seen near Black Point, Matheson Hammock, and Key Largo. A habitat assessment component includes monthly rollerframe sampling, started in 1993, of epibenthic fish and decapods to analyze potential interactions between released red drum and resident fauna. Impact of the live shrimp fishery on target and nontarget species is also assessed. A fishery-independent component works to develop quantitative methodologies and analyses on hatchery production and post-release population dynamics. Biscayne Bay habitat is generally suboptimal for red drum less than 100 mm total length, and there are heavy losses to predation, especially to barracuda and redfin needlefish. (Ault et al. 1995; Capo and Wisner 1995; Serafy 1995; UM 1995)

FIU

Analysis of DERM seagrass monitoring program. Under a subcontract in conjunction with NMFS' development of an optical water quality model for seagrasses in Biscayne Bay, FIU is conducting a historical analysis of seagrass density and biomass at long-term epibenthic monitoring stations in the Dade DERM seagrass habitat program. Objectives are to assess adequacy of the program for detecting trends in specific seagrass populations in the bay, report on long-term and seasonal trends, and assess the program's ability to detect changes in distribution in the bay as a whole. (Fourqurean 1995; Kenworthy and Schwarzschild 1994a)

Study of *Galactia* species. The Center for Plant Conservation is funding research on four species of milk-pea (*Galactia*) in Dade pine rocklands. The project is specifically investigating population status of *G. pinetorum*, ranked globally imperiled by FNAI and a candidate for Federal protection. Abundance of all four species, including Federally endangered *G. smallii*, is being correlated with preferred habitat type through GIS analysis to determine why *G. pinetorum* and *G. smallii* are rare compared to the two common species. Results could increase success of future attempts to reestablish *in situ* populations of the rare species. (Dade DERM 1993a; O'Brien 1994)

Sea turtle nesting survey. Aerial surveys conducted over Dade Co. beaches indicated nesting increased from south to north. (Fletemeyer 1991)

Topical Audubon Society

Tern Project. TAS initiated a project in South Florida to identify actual and potential nesting sites of the least tern and implement measures to monitor, protect, and enhance these sites. The first phase was designation, in cooperation with Dade PRD, of a potential nesting site on the north side of Crandon Park marina as a protected area. Terns were observed attempting to nest here but abandoned the site because of disturbance by humans and their pets. A chainlink fence was erected around the site in May 1993 to deter feral cats and reduce pedestrian traffic, and volunteers have removed invasive vegetation and added coarse sand and shell to the site. (Goodwin undated, 1994)

Fairchild Tropical Garden

Natural areas mapping. The Garden is a partner with Dade PRD in a GIS- and GPS-based mapping effort. It is helping coordinate the development of vegetation maps and will study biology of the natural areas. (Fisher 1994)

Florida Power & Light Company

Monitoring of American crocodile at Turkey Point Nuclear Power Plant. The power plant site at Turkey Point is ideal habitat with 270 km (168 mi) of saltwater cooling canals with secure nesting berms, abundant food, and isolation from people. FPL's program began in 1978 when the finding of a dead hatchling showed breeding was occurring. In 1980, two nest sites were found on berms. In 1987 the population totaled 20-30 individuals and 10% of Florida's crocodile hatchlings were produced here. FPL protects the crocodiles with a management plan that ensures activities such as maintenance do not interfere with the animals. A monitoring program is overseen by Frank Mazzotti of UF. In 1992, there were 12 nests and 155 hatchlings. In 1993, there were 11 nests and 181 hatchlings. Biologists mark all hatchlings with tail scute notches. (Gaby et al. 1985; Garlock 1994; Van Meter 1987)

Subregion

FWS

Manatee tracking. Movements of tagged manatees have been followed by ongoing year-round satellite tracking since 1986 and radio tracking since 1978. (Dade DERM 1994a)

FDEP

Sea turtle nesting activity status. Since 1979, permits have been issued to individuals, groups, and government agencies to conduct nesting surveys. Following each year's nesting season, permit holders are requested to complete summary forms, which are compiled to assess yearly status of nesting activity throughout the state. Beaches of Subregion 9 with the longest data records are Boca Raton public beach and John U. Lloyd SRA surveyed since 1979; and Broward Co. beaches, Bill Baggs Cape Florida SRA on Key Biscayne, and Miami area beaches, surveyed since 1980. (Conley and Hoffman 1987; Harris et al. 1984)

FGFWFC

Tree snail distribution, status, and biology. The 1993 FGFWFC Nongame Wildlife Program provided funding to Univ. of Florida for a 1-year study of the historical distribution and current status of the Florida tree snail. The Univ. of Texas was funded for a 3-year study of genetic variation, systematics, and reproduction of the tree snail. (FGFWFC 1993)

Short-tailed hawk survey. During 1993-94, released hawks were tracked by radiotelemetry. A rehabilitated subadult was released in Broward and during 6 months of tracking ranged through about 100 km^2 of central Broward and urbanized Fort Lauderdale. It moved among small, isolated patches of undeveloped forest in city and county parks. A subadult released near Homestead remained in the vicinity for 2 weeks. An adult released in Coral Gables remained near Old Cutler Ridge during the 2 weeks it was monitored. This preliminary information suggests that islands of habitat have important wildlife value. (FGFWFC 1994; TAS 1994)

Fisheries monitoring. Fish populations are monitored in the canals of Dade and Broward counties east of the WCAs. Numbers and biomass are estimated based on electroshocking and block-net sampling in order to evaluate the impact of the introduced peacock bass on populations of native and non-native fish in the canals. (Haddad et al. 1995)

FIU

Impacts of coastal development on turtle nesting in Broward and Palm Beach counties. A multifaceted study with many projects was initiated as early as 1974 over an 87-km (54-mi) section of beach that represents one of the world's most heavily developed coastal areas with a large population of nesting sea turtles. Human disturbance and development were quantified by a coastal inventory that was compared to nesting survey data. Natural predation, poaching, boat-related mortality, effects of beach cleaning and nourishment, and other disturbance variables were assessed. Nesting generally increased from south to north in the study area. Loggerheads nest throughout the area, and juvenile and adult green turtles are relatively common. Observations showed that the shallow coastal area off Broward and Palm Beach counties is major developmental habitat for juveniles. Juvenile hawksbills were commonly seen by divers on the shallow reefs. Numerous nesting adults and hatchling leatherbacks were seen. A Kemp's ridley turtle was observed attempting to nest in Palm Beach Co., but it did not lay eggs. This observation is the first record of a nesting Kemp's ridley on the Atlantic coast. It was concluded that a beach safe for turtle nesting had a minimum number of human disturbances and a relatively steep slope. Recommendations included: limit or prohibit night pedestrian traffic on nesting beaches; construct high-profile, vegetated dunes as buffers from highways; prevent operation of mechanical beach cleaning equipment during nesting and hatching season; allow nests to incubate naturally and discontinue nest relocation programs except in emergencies; aggressively enforce limits on beach lights; limit use of lights on piers; conduct education programs to discourage beachfront lighting and dumping of plastic and other debris. (Fletemeyer 1990, 1991)

Fairchild Tropical Garden

Endangered plant propagation. The Garden propagates plants for the Center for Plant Conservation and maintains a conservation collection of 11 species of South Florida endangered flora. Those that occur in Subregion 9 are the crenulate lead-plant, Small's milkpea, and beach jacquemontia. The rare Biscayne prickly-ash is also being cultivated. Horticultural practices are being developed for successful maintenance of wild plants and for enriching the genetic representation of the collection. Also being developed are plans for reintroducing endangered plants and identifying native habitats for experimental reintroductions and *in situ* conservation of species. (Garvue 1994; FWS 1990; Johnson et al. 1993)

National Audubon Society

Breeding bird survey. NAS conducted a nationwide survey of breeding bird populations to verify presence or absence of nesting by species. Sampling conducted in Florida during 1986-91 included the three counties of Subregion 9. Each county had its own survey coordinator. Verification of Florida data was expected to be completed in 10/94. The Florida atlas will be not be published before the end of 1995 or 1996. (H. Kale, Florida Audubon Soc., pers. comm.)

Butterfly World

Research and breeding of lepidopterans. Butterfly World, in Tradewinds Park in Broward, is a captive breeding and research laboratory, along with an educational facility. Research has included cooperative work with Univ. of Florida on effects of mosquito-control pesticides on butterflies and other insects, particularly in the Florida Keys. Thousands of larvae were raised for the research. Captive breeding of the Schaus' swallowtail was proposed. (Emmel and Boender 1991)

SCIENCE INFORMATION TRANSFER

Dade County

SFWMD

Hispanic community outreach program. In 12/92, SFWMD began a program targeted at the Dade Hispanic community to inform them about South Florida's water resources and what they can do to protect those resources. One component uses various communication media, including a celebrity spokesperson, to target the adult community. A second component targets Hispanic youth, ages 5-12, to protect Biscayne Bay in projects such as bay cleanups, pollution prevention, shoreline stabilization, etc. Another planned component is to implement a water resources awareness campaign aimed at Hispanic community leaders. By targeting community leaders, SFWMD hopes to educate the community at large on how they can shape Dade's water resource future, given the county's growth rate and demand on the resources, and how people's individual and collective actions affect these resources. (SFWMD 1994b)

Biscayne Bay Environmental Education Program. Several projects have been carried out through grants from SFWMD and Dade Co., associated with the SWIM program, including development of teaching materials and education programs and production of television public service announcements about problems such as littering. The Miami River Coordinating Committee and Biscayne National Park have also been partners. Baynanza, an annual celebration established in 1982, is a major event to focus public attention on environmental, historic, cultural, aesthetic, and recreational values of Biscayne Bay. Five new projects are proposed: conduct a campaign to make children aware of bay resources and need for protection; implement Cape Florida interpretive project about habitat restoration; develop a speakers bureau to make business owners aware of the importance of good water quality in the bay; initiate wetland education programs for secondary school students; and prepare a guide to supplement existing middle school environmental education programs. Watershed planning projects, such as for Arch Creek, Miami River, and South Dade Co., involve educating stakeholders and reaching consensus on solutions. (Alleman et al. 1995a,b; Biscayne Bay Manage. Comm. undated(b); SFWMD 1995)

Dade Co. DERM

Public information campaign on invasive plants. DERM is working with the FLEPPC and State Cooperative Extension Service to educate the public about pest plants, including how they spread and how to eradicate them on a species-by-species basis. Workshops on safe and selective use of herbicides are also held. (Coop. Ext. Serv. undated)

Subregion

Fairchild Tropical Garden

Endangered plant exhibit. An exhibit of live rare plants is planned to educate the visiting public. The display will characterize the plants' native habitats and show what is needed to ensure their recovery. (Garvue 1994)

SUBREGION 10:

CALOOSAHATCHEE RIVER BASIN AND SOUTHWEST FLORIDA

INTRODUCTION

Subregion 10 encompasses the Caloosahatchee River watershed, the lower Charlotte Harbor estuarine ecosystem and coastal system south to Naples Bay, the Corkscrew Regional Ecosystem Watershed, and the Immokalee Rise. The subregion includes Lee County, western Collier and Hendry counties, southern Glades County, and southeastern Charlotte County (Figure 1).

This chapter summarizes the major ecological and hydrological issues, problems, and threats in Subregion 10; existing scientific information on these topics; and ongoing and proposed science projects. It identifies scientific information gaps and the studies needed to fill theses gaps. The purpose of this task, and the Science Subgroup, is to provide the necessary scientific information to develop and implement management strategies to restore impacted ecosystems to a naturally functioning, self-sustaining state and to prevent further ecosystem degradation. The task was accomplished by meeting with scientists who work in this subregion and reviewing the scientific literature.

BACKGROUND

As occurs in most of Florida, the human population in Subregion 10 is concentrated along the coast, which is rapidly becoming highly urbanized. This coastal zone had the highest growth rate in Florida over the last 10 years and has the highest projected growth rate from now to 2010. The Cape Coral-Fort Myers and Naples metropolitan areas are among the seven fastest growing in the U.S. In the 1980s, Collier and Lee County populations grew by 77% and 63%, respectively (SFWMD 1992). Projected population increases for Collier and Lee Counties from 1990-2010 are 140% and 90%, respectively (SFWMD 1992).

A somewhat unique aspect of this subregion is large-scale "planned" residential development projects, which were constructed from the late 1950s to the early 1970s. Cape Coral, Lehigh Acres, and Golden Gate Estates are the largest of these developments. Cape Coral is the second largest Florida city in area (285 km^2; 110 mi^2). The natural habitats in over 90% of this area were destroyed; wetlands were filled and terrestrial forests were cleared of vegetation. Over 2000 km (1242 mi) of roads and 650 km (404 mi) of freshwater and estuarine residential canals were constructed. During this process most of the land was platted and sold as residential home sites. The projected build-out population of Cape Coral is 400,000 people. Population today is 80,000-100,000. Many areas of the city are sparsely populated; however, Cape Coral is one of the five fastest growing cities in the country. The environmental impacts of such "mega" developments are discussed below.

Agriculture is a major land use in the interior of Subregion 10. This subregion probably has the State's highest rate of land conversion to agriculture, primarily citrus. In the 1980s, irrigated agricultural acreage in Collier and Lee Counties increased by 99% and 35%, respectively (SFWMD 1992). From 1984-1994, citrus acreage in Southwest Florida (Lee, Collier, Hendry, Glades, and Charlotte Counties) grew from 17,000 ha (42,000 acres) to 72,000 ha (178,000 acres), an increase of 320% (FASS 1994). This boom in acreage is the result of interregional movement of citrus farming from Central to Southwest Florida following several severe freezes in the mid-1980s. Projected increases in citrus acreage for Collier, Hendry, Glades, and Lee counties from 1990-2010 are 150%, 100%, 90%, and 50%, respectively (SFWMD 1992). Environmental implications of this conversion are discussed below.

Caloosahatchee River Watershed

The river basin drains an area of about 3700 km^2 (1429 mi^2). The basin extends from Lake Okeechobee to the river mouth in San Carlos Bay. The watershed includes northern Lee and Hendry Counties, southern Glades County, and southeastern Charlotte County.

The Caloosahatchee River was originally a shallow meandering stream about 80 km (50 mi) long with headwaters near Lake Hicpochee (Drew and Schomer 1984; Hammett 1990). The river was extended east to Lake Okeechobee by dredging in 1884, and it was first channelized to improve navigation and flood control in the 1930s. Three locks or water control structures were constructed on the river: Moore Haven Lock and Ortona Lock in 1937, and Franklin Lock, near Olga, in the 1960s. Franklin Lock acts as a salinity barrier. The freshwater portion of the river is 60 km (37 mi) long; the tidal Caloosahatchee extends downstream of Franklin Lock for about 45 km (28 mi). Most of the freshwater entering the Caloosahatchee estuary is through Franklin Lock. There are 60 tributaries to the Caloosahatchee River; many are channelized.

The most common land uses in the freshwater portion of the basin are agriculture and rangeland; the tidal basin is primarily urbanized.

Charlotte Harbor Estuarine Ecosystem

The Charlotte Harbor estuarine system includes Charlotte Harbor proper; Pine Island Sound; Matlacha Pass; San Carlos Bay; an extensive barrier island system; and the tidal reaches of the Caloosahatchee, Peace, and Myakka Rivers. The estuary is the second largest in Florida with a surface area of 700 km^2 (270 mi^2). The watershed is about 12,140 km^2 (4687 mi^2) (Hammett 1990). There are five NWRs, four State aquatic preserves, and two State land preserves within the system. Only the southern half of the system is in the SFWMD and technically part of Subregion 10; the northern half is in the SWFWMD. Management implications of this political division are discussed below.

The system is a shallow, subtropical, coastal plain estuary with an overall mean depth of about 2 m (6.6 ft). Water depths in the northern portion are 0.5-1 m (1.6-3.3 ft) greater than the southern. The estuary is separated from the Gulf of Mexico by a series of large barrier islands. Total average discharges to Charlotte Harbor from the Caloosahatchee, Peace, and Myakka rivers are 2000 cfs, 2000 cfs, and 630 cfs, respectively (Hammett 1990). Direct rainfall contributes about 1000 cfs. The water column is usually partially to thoroughly mixed due to the shallow depths and moderate freshwater inflows (SWFWMD 1993).

Seagrass and benthic macroalgae are abundant in Pine Island Sound and Matlacha Pass. Deeper Charlotte Harbor proper has fewer benthic macrophytes and primary productivity is plankton based. The system provides habitat for over 30 threatened or endangered species and supports highly productive fisheries.

Estero Bay Estuary and Watershed

This system in southwestern Lee County consists of Estero Bay and associated barrier islands, the Estero Bay basin including the Imperial and Estero Rivers, and the Six Mile Cypress Slough Watershed.

Estero Bay is a shallow, subtropical lagoon (4580 ha; 11,317 acres) separated from the Gulf by barrier islands. Seagrass beds are common in the bay, but high turbidity restricts seagrasses to shallow depths (Lee County 1994). Estero Bay differs from Charlotte Harbor in that there are no significant rivers flowing into it and only weak tidal exchange due to restricted inlets (Godschalk and Assoc. 1988). Lands surrounding Estero Bay, including the barrier islands, are highly developed. Estero Bay is a State aquatic preserve.

Six Mile Cypress Slough (830 ha; 2050 acres) is characterized by dense cypress interspersed with numerous ponds. The slough has been preserved through Florida's SOR Program (SFWMD 1993a).

Corkscrew Regional Ecosystem Watershed

The CREW is 23,500 ha (58,069 acres) of mostly functional wetlands in southeast Lee and north Collier Counties. The watershed contains a variety of habitat types and plant communities, the most common being cypress sloughs (CREW Trust 1992). The 4460-ha (11,021-acre) Corkscrew Swamp Sanctuary, operated by NAS, is part of this watershed. The Sanctuary has North America's largest nesting colony of endangered wood storks and largest remaining stand of virgin bald cypress (Duever et al. 1974; Browder 1984). The CREW provides habitat for about 75 endangered or threatened plant and animal species (CREW Trust 1992).

The CREW has significant hydrologic importance to the region. It conveys water to Florida Panther NWR, Fakahatchee Strand State Preserve, and the Estero Bay State Aquatic Preserve Watershed. The CREW is on the approved projects acquisition lists of the State SOR and CARL programs. Since 1989, 5670 ha (14,010 acres) have been acquired (CREW Trust 1992). Most of the land surrounding the CREW has been converted to agriculture (Immokalee Rise agricultural area). Winter vegetables are the primary crop, but citrus is increasing.

Hydric Pine Flatwoods

The hydric pine flatwood ecosystem is characterized by a slash pine-dominated (*Pinus elliottii*) upperstory and wetland plant understory (Beever and Dryden 1993). The longer hydroperiod and wetland understory differentiate this ecosystem from xeric and mesic pine flatwoods. Only recently have scientists and government regulatory agencies recognized hydric pine flatwoods as a separate community or ecosystem type. Hydric pine flatwoods covered at least 81,000 ha (200,151 acres) in Southwest Florida in 1989 (Beever and Dryden 1993). This ecosystem type also occurs in Subregion 3 (in Martin and Palm Beach counties).

The hydric pine flatwoods of Southwest Florida have regionally significant ecological and hydrological value. Plant species diversity is high: over 900 species, including 85 protected species (Beever and Dryden 1993). At least 21 Federal and State listed animal species utilize this ecosystem. Hydric pinelands are thought to be important to groundwater recharge (Beever and Dryden 1993).

MAJOR ISSUES

Alteration of Natural Freshwater Inflow to Estuaries

As elsewhere in South Florida, the natural pattern (quantity and timing) of freshwater inflow to estuarine ecosystems in this subregion has been altered by anthropogenic activities. These activities include channelization and water control structures for flood control, dredging for navigation, wetland drainage and filling, and urban and agricultural land development.

Caloosahatchee Estuary

The natural pattern (quantity and timing) of freshwater flow into the Caloosahatchee estuary has been disrupted due to its unnatural connection to Lake Okeechobee, water control structures on the river, the network of channelized tributaries and drainage canals in the basin, and urban and agricultural water demands (Drew and Schomer 1984; Hammett 1990; SFWMD 1993b). Periodic regulatory releases from Lake Okeechobee are made to the estuary via the river. During such releases the volume of freshwater entering the estuary can be >10,0 cfs (SFWMD 1993b). These releases usually occur during the latter part of the dry season when freshwater flow would naturally be lowest. Because of these discharges the freshwater flow into the estuary exceeds the historical volume, especially in the dry season. Conversely, when regulatory discharges are not occurring, unnaturally low freshwater inflow can occur during the dry season due to high water demand for agricultural and urban uses (SFWMD 1993b). The network of channelized tributaries and drainage canals exacerbates the excessive discharge problem.

Several studies indicate this altered flow pattern impacts the Caloosahatchee Estuary. Discharges >6000 cfs from Franklin Lock cause the entire estuary to become oligohaline and can decrease salinity in the outer

embayments, San Carlos Bay and Matlacha Pass (Chamberlain 1992; Bierman 1993). Submerged vegetation in the estuary has decreased significantly since installation of Franklin Lock (McNulty 1972; Harris et al. 1983; SFWMD 1993b). Other studies suggest impacts on water quality, benthic fauna, and fisheries (summarized in SFWMD 1993b).

Spreader Waterways and Cape Coral

The concept of "spreader waterway" was developed as a mitigation technique to reestablish sheetflow of water in wetlands that are anthropogenically altered. Spreader systems seem most common in Southwest Florida. The largest system, with 40 km (25 mi) of spreader waterways, is in Cape Coral.

The condition and function of the Cape Coral spreader system was recently evaluated (Morrison et al. 1990). Construction of the 650-km (404-mi) Cape Coral residential canal system altered the natural freshwater sheetflow pattern into Matlacha Pass (Charlotte Harbor). Two spreader waterways were constructed to reestablish sheetflow in the late 1970s. The spreader system is not functioning properly (Morrison et al. 1990). There are numerous breaches resulting in channelized freshwater flow into Matlacha Pass. This channelized inflow has eliminated or degraded seagrass and mangrove habitat and reduced seagrass productivity. Dysfunctional spreader systems, such as that at Cape Coral, make the effectiveness of this mitigation method questionable.

Faka Union Bay and Golden Gate Estates

Construction of the Faka Union and Golden Gate Estates canal systems altered natural freshwater sheetflow into Faka Union Bay and adjacent estuarine areas (Browder et al. 1989; SFWMD 1994). The canal systems increase the rate of surface water runoff, resulting in substantial point loads of freshwater into the estuaries. This alteration has had the following effects on the estuarine ecosystem: altered natural salinity regime and freshwater shocks; decreased nursery value for fish and shellfish by reducing the area with salinity ranges favorable for planktonic and juvenile forms; reduced abundances of subadult and adult fish; increased nutrient loading; and long-term negative effects on habitat quantity and quality, including likely decline in seagrass coverage (Browder et al 1989; SFWMD 1994).

Charlotte Harbor Estuarine Ecosystem

The environmental quality of Charlotte Harbor is generally considered to be better than most Florida estuaries. Significant habitat loss and water quality degradation, however, have occurred over the last 30-50 years.

Seagrass and saltmarsh acreage decreased 29% (99 km^2; 38 mi^2) and 51%, respectively, from 1945-1982 (Harris et al. 1983). However, mangrove forest acreage appears to have increased 10% during this period. Additional seagrass and saline marsh loss and alteration occurred from 1982-1990 (Morrison et al. 1990; R. Repenning, FDEP, pers. comm.; L. Riley, Lee Co., pers. comm.). Submerged vegetation in the lower Caloosahatchee estuary has decreased significantly since installation of Franklin Lock (SFWMD 1993b). These losses are attributed to anthropogenic activities, especially large land development projects, causeway construction, and alteration of freshwater inflow patterns.

Nutrient loads, especially nitrogen, entering the estuary have been increasing for the past 15-20 years. Nitrogen and phosphorus inputs via the Caloosahatchee River and nitrogen input from the Peace River have risen (McPherson and Miller 1990; Hammett 1990). Increased urban, especially wastewater treatment plants, and agricultural development account for the greater nutrient loading. Furthermore, urban growth alone is predicted to enlarge nitrogen loading by 20% by the year 2020 (Hammett 1990). Primary production in the estuary appears to be nitrogen limited (Montgomery et al. 1991; McPherson and Miller 1990). The projected increased nitrogen loads favor undesirable growth of phytoplankton and benthic algae (McPherson and Miller 1990).

Turbidity has probably increased in lower Charlotte Harbor due to alteration of the estuary bed from dredge-fill activities and seagrass loss (Harris et al. 1983). Suspended, nonchlorophyll particulate matter is the primary cause of water column irradiance attenuation in the estuary (McPherson and Miller 1987). Thus, light reaching benthic vegetation has likely decreased in recent years. Irradiance may limit benthic vegetation growth in

parts of the estuary, especially deeper water (McPherson and Miller 1987). Predicted greater phytoplankton density with increased nitrogen loading would further decrease irradiance and inhibit seagrass growth.

Mosquito pesticide application (aerial spraying) is conducted extensively in the Charlotte Harbor system. Lee County has one of the largest mosquito control programs in the country. There is concern and debate about potential ecological impacts of mosquito pesticide application in the mangrove ecosystem. Temephos (Abate), a larvicide, is used in the estuary, including the NWRs. Temephos can be toxic to aquatic invertebrates, especially crustaceans (Clark 1991). However, Pierce et al. (1989) did not observe acute toxicity to five species of crustaceans and fish exposed to a field application of temephos in Charlotte Harbor. Temephos can persist for several days (Clark 1991). FDEP does not permit temephos application on designated aquatic preserves in Charlotte Harbor. The FWS has recently ordered Lee County Mosquito Control to cease spraying temephos on NWRs. Fenthion (Baytex), an adulticide, is also used in Lee County around Charlotte Harbor. It is very toxic to marine invertebrates (Clark 1991). There is concern about drift of fenthion into mangroves. Faunal mortalities in State aquatic preserves may have been caused by fenthion drift (B. Repenning, FDEP, pers. comm.). The aquatic half-life of fenthion is 4-7 days (Clark 1991). No field studies on chronic or sublethal effects of fenthion have been conducted (Clark 1991).

Low DO levels, high chlorophyll *a* concentrations, and high sediment metal concentrations have been reported in the tidal Caloosahatchee (DeGrove and Nearhoof 1987; SFWMD 1993b). However, water quality data for the tidal Caloosahatchee are insufficient for temporal analysis (DeGrove and Nearhoof 1987).

The numerous residential canal systems that feed into the estuary likely contribute to estuarine water quality degradation. For example, the 250-km (155-mi) estuarine portion of the Cape Coral canal network has significantly poorer environmental quality (lower DO and benthic invertebrates; higher nutrients, sediment metals, and turbidity) than the Caloosahatchee estuary (Morrison 1989).

Freshwater Caloosahatchee River

The freshwater Caloosahatchee is a severely stressed ecosystem, with substantial water quality problems. State water quality standards have been frequently exceeded (DeGrove and Nearhoof 1987). Water quality problems include: low DO; high nutrients (total nitrogen usually >1.5 mg/L, total phosphorus usually >0.1 mg/L); high chlorophyll *a* and undesirable algal blooms; high water column pesticide and metal concentrations; and high metal levels in sediment and invertebrates (DeGrove and Nearhoof 1987; J. Cassani et al., Lee County, unpublished data). Specific conductance increased and ionic composition changed between the 1940s and 1980 (LaRose and McPherson 1983). Lake Okeechobee discharge and basin runoff contribute pollutants to the river; however, there is conflicting information on which source most affects river water quality (CDM 1991a).

Estero Bay Estuary and Watershed

Water quality in Estero Bay is generally considered to be fair to good; however, degradation has occurred in recent years (Godschalk and Assoc. 1988; Lee Co. 1994). Nutrient and turbidity levels have increased. Estero Bay sediments are enriched in cadmium, lead, and zinc. The freshwater inflow pattern has been altered. Water quality problems are attributed to increased urbanization of the watershed and, for turbidity, increased boat traffic. Watershed urbanization was projected to increase by over 130% (based on number of dwelling units) from 1986-2010 (Godschalk and Assoc. 1988). Environmental quality in Estero Bay is particularly vulnerable to future degradation due to poor flushing, the bay's low volume, and increasing urbanization of the watershed (Godschalk and Assoc. 1988).

The natural hydroperiod and water flow pattern in Six Mile Cypress Slough has been altered (Lee Co./ SFWMD 1988; SFWMD 1993a). Exotic plant invasion is a problem (SFWMD 1993a; Lee Co. 1994). The southern third of the slough is heavily infested with melaleuca (*Melaleuca quinquenervia*); exotic control and reforestation efforts are ongoing in the slough.

Citrus Development and Other Agricultural Issues

As discussed above, there has been and will continue to be considerable conversion of uplands and pasture lands in Subregion 10 to citrus. Much of the current and proposed citrus development occurs in an area with diverse fauna and flora, including 31 Federal and State protected species (Mazzotti et al. 1992), and adjacent to valuable wetlands. There is concern about potential effects of citrus development on plants, wildlife, and their habitats and on surface and groundwater quality and quantity. For example, some citrus development projections estimate that up to 50% of available habitat for the endangered Florida panther in the Immokalee Rise area may be lost (Mazzotti et al. 1992). However, there are few studies that evaluate possible impacts.

Citrus has lower biological habitat value than pasture, upland, and wetlands -- the habitats most likely to be converted to citrus. Most species occurring in citrus groves inhabit agricultural reservoirs, temporary ponds, or seasonal wetlands in groves. In addition to habitat loss, another consequence of citrus conversion is fragmentation of remaining high-quality habitat (Mazzotti et al. 1992). Mazzotti et al. (1992) developed and evaluated alternatives for integrating biological conservation and citrus development in Southwest Florida.

Agriculture dominates water use in the interior of Subregion 10 (SFWMD 1992). Citrus uses more water per acre than any other type of agriculture, except plant nurseries (Hammett 1990). More water use permits are issued for citrus than any other agricultural type (Mazzotti et al. 1992). From 1990-2010, water demand by citrus in Collier, Glades, Hendry, and Lee Counties is projected to increase 130%, 80%, 70%, and 35%, respectively. Citrus farming causes lower water tables, which impacts hydrology and the structure and function of wetlands (SFWMD 1992).

Employing BMPs will likely reduce pollutant export via surface runoff from citrus groves. Greater than 95% of nutrients and 99% of pesticides applied to a grove with wet detention systems were retained on site (Sawka et al. 1994).

Corkscrew Regional Ecosystem Watershed

All lands around the CREW are undergoing intense development pressure from agriculture and other land uses (CREW Trust 1992). Much of the surrounding land has been converted to agriculture, mainly vegetables but more recently citrus. The ecological and hydrological effects on the CREW are not known.

Two municipal wellfields have cones of influence that extend into the CREW (CREW Trust 1992). There is concern that these wellfields are lowering groundwater and surface water in CREW wetlands, affecting wetland hydrology and ecology. A SFWMD contract study is evaluating the potential impacts of wellfield withdrawal (CREW Trust 1992).

Pine flatwoods in parts of the CREW were clear cut in 1989-90 for conversion to citrus. However, SFWMD has acquired this land, and natural reforestation is taking place (CREW Trust 1992). Invasive exotic plants, especially melaleuca and Brazilian pepper (*Schinus terebinthifolius*), pose a serious ecological threat if not controlled. Oil exploration occurs in the CREW. Residential development adjacent to CREW is increasing.

A SFWMD contract project assessing CREW hydrologic, hydrogeologic, and biological resources was recently completed (Gee and Jenson 1993). This study provides strategies for protecting CREW ecological and hydrological resources.

Hydric Pine Flatwoods

Slash pine forest acreage in Southwest Florida declined 88% from 1900-1989 (Mazzotti et al. 1992). Noss et al. (1995) list slash pine forests in Southwest Florida as one of the endangered ecosystems in the U.S. Large acreages of hydric pine flatwoods have been lost to logging, development, and agricultural activities (Beever and Dryden 1993). Habitat destruction from residential and commercial development and citrus conversion continues.

Melaleuca and other invasive exotic plants are a serious ecological problem. Anthropogenic activities alter natural surface and groundwater hydrology. Drainage of hydric pinelands greatly increases susceptibility to exotic plant invasion (Wade et al. 1980).

Naples Bay Ecosystem

The Naples Bay estuarine ecosystem includes Naples Bay, Gordon River, Rock Creek, Haldemen Creek, and Gordon Pass. Water quality in this system has degraded (Collier Co. 1993a). Water quality problems include high nutrient levels (especially ammonia), high chlorophyll *a*, low DO, and high fecal coliform bacteria. State water quality standards have been frequently violated, especially bacteria levels. Water quality problems are partially attributed to increased urbanization of the watershed.

CURRENT SCIENCE ACTIVITIES

Ongoing, planned, and proposed science projects, as related to issues identified in the previous section, are listed below by agency or organization.

Alteration of Freshwater Inflow to Estuaries

Caloosahatchee Estuary

SFWMD

Recently developed a research plan that addresses the Caloosahatchee estuary freshwater inflow problem (SFWMD 1993b). Objectives of the plan are to: 1) determine the optimal freshwater inflow range (quantity and timing) that provides the salinity gradient necessary for healthy biological communities; 2) develop "real-time" field monitoring and management capabilities; 3) establish estuarine water quality and nutrient loading limits; and 4) protect listed species. Ongoing or proposed science activities include:

- Evaluation of alternative Lake Okeechobee release schedules (includes developing ecological performance measures based on indicator species).
- Salinity modeling and monitoring.
- Biota assessments.
- Water quality and basin nutrient loading assessments.

If implemented as proposed, this program should provide the necessary scientific information to facilitate restoration of an appropriate freshwater flow pattern into the tidal Caloosahatchee. However, the indicator species approach outlined in the plan should be independently evaluated. The use of other ecosystem attributes, such as landscape features, to optimize salinity patterns should also be evaluated. SFWMD should immediately establish a comprehensive water quality monitoring program in the Caloosahatchee estuary, as exists in the St. Lucie estuary (Germain 1994).

Charlotte Harbor System

SWFWMD

- Identification of optimal freshwater flows, for SWFWMD portion only (SWFWMD 1993).

USGS

- Salinity distribution and model related to freshwater inflow.

Faka Union Bay and Golden Gate Estates

SFWMD

- Development of a hydrologic restoration plan (SFWMD 1994) for southern Golden Gate Estates with the goals to: 1) restore wetland hydroperiod and surface water sheetflow; 2) restore more natural freshwater inflow pattern to estuaries; 3) improve groundwater recharge; 4) enhance surface water deliveries to Fakahatchee Strand; and 5) reduce overdrainage of Fakahatchee Strand and Florida Panther NWR lands.

Collier County

- Surface and groundwater quality monitoring in Golden Gate Estates and Faka Union Canal system (Collier County 1993b).

Charlotte Harbor Estuarine Ecosystem

SWFWMD (For SWFWMD portion only; see SWFWMD 1993 for description.)

- Water quality monitoring program.
- Development of resource-based water quality targets and pollutant load reduction goals.
- Habitat mapping and assessment.
- Toxics assessment
- Diagnostic watershed assessment: quantification of point and nonpoint source pollution.

SFWMD (For Caloosahatchee Estuary only; see SFWMD 1993 for description.)

- Water quality and basin nutrient loading assessments.
- Salinity modeling and monitoring.
- Biota assessments.

USGS

- Charlotte Harbor Environmental Assessment Program (see SWFWMD 1993 for description); only work left is completion of the following project reports:
  - Tidal flow, circulation, and flushing characteristics.
  - Salinity distribution and model related to freshwater inflow.
  - Physical, chemical, and biological characteristics under present and future environmental conditions.

FMRI (M. Mitchell, pers. comm.)

- Fisheries-independent monitoring program: provide long-term database on juvenile fish abundance and fisheries abundance trends.
- Seagrass and other habitat mapping: currently conducting habitat change analysis for 1982-1992.
- Assessment of seagrass damage by boat propeller scarring.
- Functional assessment of seagrass beds: includes assessment of fish and invertebrate assemblages.
- Long-term seagrass monitoring: detailed *in situ* monitoring of seagrass distribution, composition, abundance, and productivity.

FWS

- Migratory bird inventories (NWRs, ongoing)

- Potential impacts of mosquito pesticide spraying on living resources and FWS lands (Ecological Services, proposed).

Mote Marine Laboratory

- Sublethal effects of mosquito pesticides on nontarget organisms.

FGFWFC

- Bird rookery inventories

City of Cape Coral (C. Jarvis, pers. comm.)

- Water quality monitoring of Cape Coral canal system.

Lee County (L. Riley, pers. comm.)

- Development of a surface water management plan that will include water quality monitoring.
- Seagrass and wetland habitat mapping and trend analysis (GIS-based).

Freshwater Caloosahatchee River

SFWMD

- Water quality monitoring at locks (see Germain 1994).
- Development of a basin assessment for the river upstream of Franklin Lock (contract with Camp, Dresser, and McKee). Phase One has been completed and includes literature review (CDM 1991a), documentation of point and nonpoint pollution sources (CDM 1991b), hydrologic model selection (CDM 1991c), monitoring program design (CDM 1992a), and QA/QC plan (CDM 1992b). The pollutant source documentation (CDM 1991c) is inadequate because CDM conducted only a one-day, qualitative field survey. Phase Two will entail water quality and quantity monitoring and data analysis. Phase Three will include entering collected data into the SFWMD GIS database, computer modeling, and developing management recommendations.

Lee County (J. Cassani, pers. comm.)

- Water quality, aquatic macrophyte, and benthic invertebrate monitoring or surveys by the Aquatic Plant Control Division.

USGS

- Water quality and other studies as part of the NAWQA Program (McPherson 1994).

Estero Bay Estuary and Watershed

Lee County

- Water quality monitoring in southern Estero Bay.
- Hydrologic study of Six Mile Cypress basin as part of Lee County Surface Water Master Plan.
- Water quality monitoring in Six Mile Cypress Slough Preserve.
- Effectiveness of various herbicide treatments to control exotic plants in Six Mile Cypress Slough Preserve.

Citrus Development and Other Agricultural Issues

SFWMD

- Contracted comprehensive environmental assessment of preserved and created wetlands within a citrus development in Caloosahatchee basin (Gator Slough). Data collection complete; report in preparation.

FWS

- Proposal to investigate environmental contaminant (nutrient, pesticide, metal) inputs and effects to Florida Panther NWR from agricultural runoff (D. Morrison and K. Edwards, unpublished proposal).

IFAS

- Proposal to assess water quality of agriculture runoff flowing into CREW, to determine effectiveness of wet detention areas to improve water quality of agriculture runoff, and to modify and verify a computer model for assessing hydrologic and water quality effects of citrus grove design and management practices (J. Capece, unpublished proposal).

Corkscrew Regional Ecosystem Watershed

SFWMD

- Contract study to ascertain CREW hydrologic, hydrogeologic, and ecological resources. Study included projects to evaluate impacts of adjacent wellfields, develop monitoring network and baseline data, inventory and map (GIS) plant communities and habitat types, integrate habitat types and their water needs, and develop strategies to protect CREW hydrological and ecological resources (CREW Trust 1992). Recently completed (Gee and Jenson 1993).

IFAS

- Proposal to assess water quality of agriculture runoff flowing into CREW, determine effectiveness of wet detention areas to improve water quality of agriculture runoff, and modify and verify a computer model for assessing hydrologic and water quality effects of citrus grove design and management practices (J. Capece, unpublished proposal).

FGFWFC

- Wildlife surveys, including population censuses of game and nongame species (CREW Trust 1992).

Lee County

- Development of surface water management program, which will include water quality monitoring.

Naples Bay Ecosystem

Collier County

- Limited water quality monitoring.

INFORMATION NEEDS

The goal, objectives (based on SSG 1993), and scientific information needs for ecosystem restoration in Subregion 10 are summarized in Figure 19. Information needs are listed in detail in the following discussion.

Alteration of Freshwater Inflow to Estuaries

- Freshwater flow pattern into the tidal Caloosahatchee.
  - The indicator species approach proposed by SFWMD should be independently evaluated.
  - Use of other ecosystem attributes, such as landscape features, to optimize salinity patterns should also be evaluated.
- Work is needed on spreader waterways to determine the best design to perform intended ecological and hydrological functions.

Charlotte Harbor Estuarine Ecosystem

- A comprehensive, integrated SWIM plan for the entire system. Major science projects should also be system-wide. Two water management districts share jurisdiction for the Charlotte Harbor system, like Indian River Lagoon; however, unlike Indian River, there is no joint system-wide SWIM plan. SWFWMD has a SWIM plan for its portion, but SFWMD does not for its portion. Likewise, most SWFWMD science projects cover only SWFWMD jurisdiction. *Note*: The Charlotte Harbor system and Estero Bay have been nominated for National Estuary designation; NEP status could facilitate coordinated scientific, management, and restoration efforts.
- GIS-based habitat and land-use trend analyses for the entire system every 3-4 years.
- A water quality monitoring program for the SFWMD portion, including the tidal Caloosahatchee, to complement SWFWMD portion.
- A system-wide nutrient and other pollutant loading study (including septic tanks).
- System-wide hydrologic and circulation model (current USGS study may meet this need).
- Diagnostic watershed assessment for SFWMD part to complement that being done in SWFWMD portion.
- Nutrient limitation and dosing experiments on seagrass-seagrass epiphyte-fleshy macroalgae-phytoplankton complex, ideally in several areas of estuary.
- Irradiance limitation and sedimentation experiments on seagrass; closely coupled with nutrient limitation study.
- Predictive model of benthic vegetation change related to water quality and pollutant loading.
- Freshwater inflow studies: see previous section.
- Field and laboratory studies of chronic and sublethal effects of mosquito pesticides to nontarget species (various life stages), especially repeated applications and extended exposure.
- Mosquito adulticide drift studies and ecological effects.
- Continued efforts on alternative (nonpesticide) mosquito control methods.

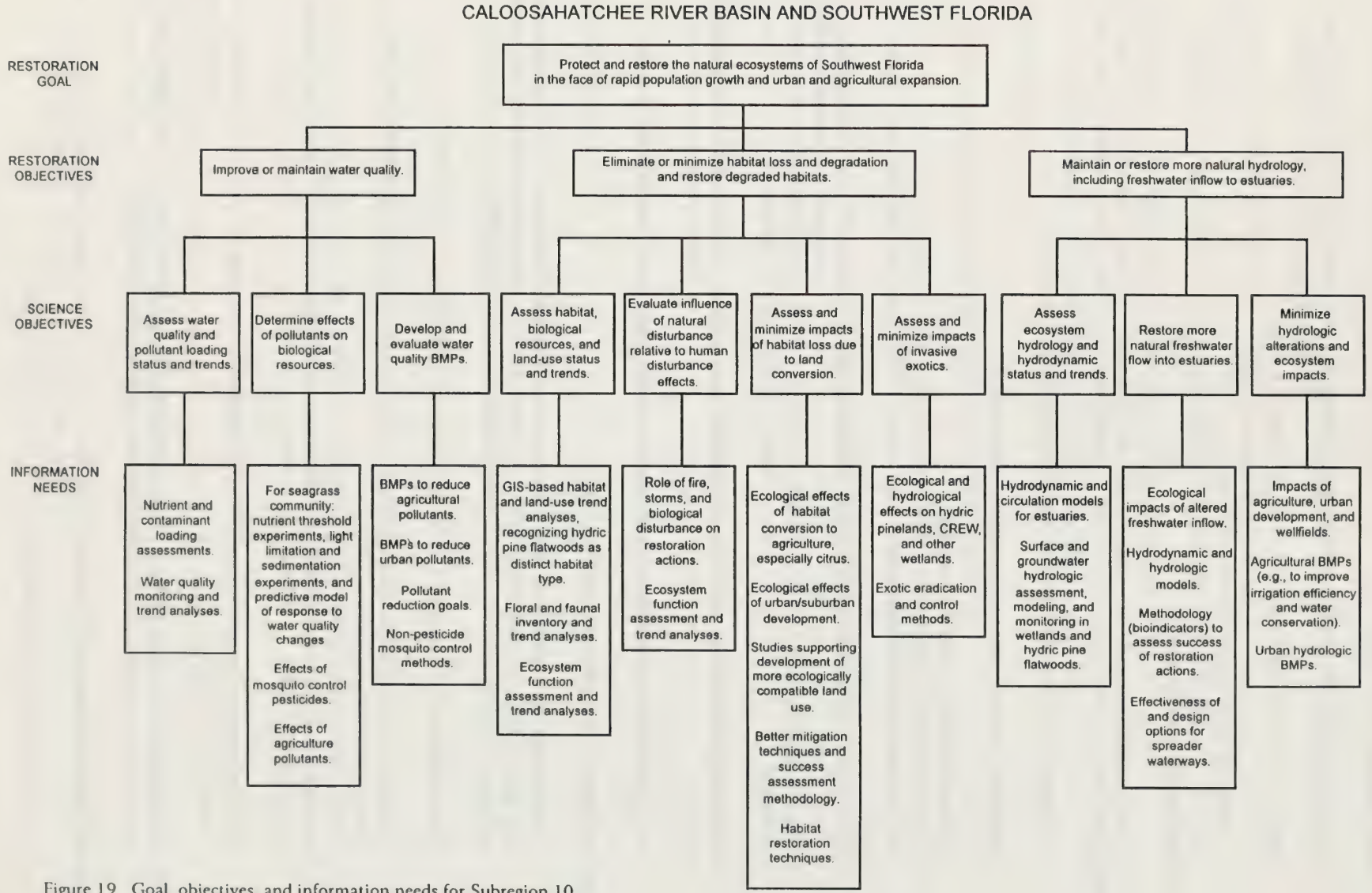

CALOOSAHATCHEE RIVER BASIN AND SOUTHWEST FLORIDA
RESTORATION GOAL
Protect and restore the natural ecosystems of Southwest Florida in the face of rapid population growth and urban and agricultural expansion.
RESTORATION OBJECTIVES
Improve or maintain water quality.
Eliminate or minimize habitat loss and degradation and restore degraded habitats.
Maintain or restore more natural hydrology, including freshwater inflow to estuaries.
SCIENCE OBJECTIVES
Assess water quality and pollutant loading status and trends.
Determine effects of pollutants on biological resources.
Develop and evaluate water quality BMPs.
Assess habitat, biological resources, and land-use status and trends.
Evaluate influence of natural disturbance relative to human disturbance effects.
Assess and minimize impacts of habitat loss due to land conversion.
Assess and minimize impacts of invasive exotics.
Assess ecosystem hydrology and hydrodynamic status and trends.
Restore more natural freshwater flow into estuaries.
Minimize hydrologic alterations and ecosystem impacts.
INFORMATION NEEDS
Nutrient and contaminant loading assessments.
Water quality monitoring and trend analyses.
For seagrass community: nutrient threshold experiments, light limitation and sedimentation experiments, and predictive model of response to water quality changes
Effects of mosquito control pesticides.
Effects of agriculture pollutants.
BMPs to reduce agricultural pollutants.
BMPs to reduce urban pollutants.
Pollutant reduction goals.
Non-pesticide mosquito control methods.
GIS-based habitat and land-use trend analyses, recognizing hydric pine flatwoods as distinct habitat type.
Floral and faunal inventory and trend analyses.
Ecosystem function assessment and trend analyses.
Role of fire, storms, and biological disturbance on restoration actions.
Ecosystem function assessment and trend analyses.
Ecological effects of habitat conversion to agriculture, especially citrus.
Ecological effects of urban/suburban development.
Studies supporting development of more ecologically compatible land use.
Better mitigation techniques and success assessment methodology.
Habitat restoration techniques.
Ecological and hydrological effects on hydric pinelands, CREW, and other wetlands.
Exotic eradication and control methods.
Hydrodynamic and circulation models for estuaries.
Surface and groundwater hydrologic assessment, modeling, and monitoring in wetlands and hydric pine flatwoods.
Ecological impacts of altered freshwater inflow.
Hydrodynamic and hydrologic models.
Methodology (bioindicators) to assess success of restoration actions.
Effectiveness of and design options for spreader waterways.
Impacts of agriculture, urban development, and wellfields.
Agricultural BMPs (e.g., to improve irrigation efficiency and water conservation).
Urban hydrologic BMPs.

Figure 19. Goal, objectives, and information needs for Subregion 10.

Freshwater Caloosahatchee River

- Basin-wide nutrient and other pollutant loading study.
- Basin-wide GIS-based habitat trend analysis every 3-4 years.
- Assessment of biological resources in river.

Estero Bay Estuary and Watershed

There is little information on the ecology and hydrology of Estero Bay. The following studies are recommended:

- Assessment of biological resources in the bay, especially seagrass beds.
- Basin-wide nutrient and other pollutant loading study.
- System-wide water quality monitoring.
- Bay circulation and flushing model.
- Watershed hydrologic study, particularly addressing altered freshwater flow into Estero Bay.
- Nutrient limitation and dosing experiments on seagrass-seagrass epiphyte-fleshy macroalgae-phytoplankton complex.
- Irradiance limitation and sedimentation experiments on seagrass, closely coupled with nutrient limitation study.
- Predictive model of benthic vegetation change related to water quality and pollutant loading.

Citrus Development and Other Agricultural Issues

- Development and evaluation of techniques to improve irrigation efficiency and water conservation (surface and groundwater). Agriculture so dominates water use in the interior that even small improvements in efficiency would result in considerable water conservation (SFWMD 1992).
- Development and evaluation of BMPs to minimize pollutants in agricultural runoff.
- Potential ecological effects of agriculture on surface and groundwater quality; ecological effects of surface water runoff from agricultural lands.
- Potential ecological and hydrological effects of lowered water table, particularly in wetlands, from agricultural activities.
- More information on potential effects of environmental contaminants (pesticides, nutrients, metals) on wildlife in citrus groves.
- Development of a system for evaluating ecological and hydrological functions that can be used to better assess predevelopment environmental conditions and success of mitigation.

Corkscrew Regional Ecosystem Watershed

- System-wide habitat trend analysis every 3-4 years (GIS-based).

- System-wide surface and groundwater quality assessment (GIS-based) (Gee and Jenson 1993).
- Ecological and hydrological effects of agriculture adjacent to CREW, especially potential nutrient and other contaminant loading from agriculture runoff.
- Examine possible hydrological and ecological impacts of oil exploration.
- Ecological and hydrological effects of residential development adjacent to CREW.
- Ecological and hydrological effects of municipal wellfields adjacent to CREW.
- Flint Pen Strand subbasin hydrologic and hydraulic study to assess the impact of new and proposed controlling structures in Kehl canal system (Gee and Jenson 1993).

Hydric Pine Flatwoods

The following recommended science needs are from Beever and Dryden (1993).

- Recognition of hydric pine flatwoods as a separate biological community type. Landscape-scale inventory and monitoring, including historical distribution and aerial coverage, temporal changes.
- Floral and faunal inventory and monitoring, including protected species. Examination of wildlife habitat value of hydric pine flatwoods.
- Ecological and hydrological effects of invasive exotics.
- Hydrologic studies including surface water hydrologic conditions needed to maintain system and groundwater recharge potential.
- Influence of fire regimes in maintaining natural plant species composition and diversity.

Naples Bay Ecosystem

- Assessment of biological resources in the bay.
- Basin-wide nutrient and other pollutant loading study.
- System-wide water quality monitoring.

Endangered and Threatened Species

- Science supporting protection and recovery of endangered and threatened species should receive higher priority in Subregion 10 relative to other subregions because this subregion has the greatest rate of urban and agricultural growth. Rapid assessment approaches may be needed.

BIBLIOGRAPHY

Beever, J.W., and K.A. Dryden. 1993. Hydric pine flatwoods of southwest Florida: a community profile. Unpublished report. FGFWFC.

Bierman, V. 1993. Draft performance report for Caloosahatchee estuary salinity modeling. SFWMD expert assistance contract deliverable from Limno-Tech, Inc.

Brandt, L.A., F.C. Depkin, and F. Mazzotti. 1992. Wildlife use of citrus groves and prairie/flatwoods ponds. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Brandt, L.A., and F.J. Mazzotti. 1992. Species habitat relationships for the Immokalee Rise area. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Brandt, L.A., L.G. Pearlstine, F.C. Depkin, W.M. Kitchens, and F.J. Mazzotti. 1992. Species models, spatial analysis of cover types, spatial projection of landscape conditions, effects of citrus conversion on selected species. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Browder, J.A. 1976. Water, wetlands, and wood storks in Southwest Florida. Ph.D dissertation. UF, Gainesville, Florida.

Browder, J.A. 1978. A modeling study of water, wetlands, and wood storks. Pages 325-346 *in* A. Sprunt IV, J.C. Ogden, and S. Winckler, editors. Wading birds. Research Report 7. NAS, New York.

Browder, J.A. 1984. Wood stork feeding areas in southwest Florida. Florida Field Naturalist 12: 81-116.

Browder, J.A, J. Tashiro, E. Coleman-Duffie, A. Rosenthal, and J.D. Wang. 1989. Documenting estuarine impacts of freshwater flow alterations and evaluating proposed remedies. Pages 300-312 *in* J.A. Kusler and S. Daly, editors. Wetlands and River Corridor Management. Proceedings of an International Symposium, July 5-9, 1989, Charleston, South Carolina. Association of Wetland Managers, Berne, New York.

Camp Dresser and McKee, Inc. 1991a. Caloosahatchee River basin assessment: Phase 1, literature review. Report to SFWMD, West Palm Beach, Florida.

Camp Dresser and McKee, Inc. 1991b. Caloosahatchee River basin assessment: Phase 1, Point and nonpoint source assessment. Report to SFWMD, West Palm Beach, Florida.

Camp Dresser and McKee, Inc. 1991c. Caloosahatchee River basin assessment: Phase 1, Model selection. Report to SFWMD, West Palm Beach, Florida.

Camp Dresser and McKee, Inc. 1992a. Caloosahatchee River basin assessment: Phase 1, Monitoring program design. Report to SFWMD, West Palm Beach, Florida.

Camp Dresser and McKee, Inc. 1992b. Caloosahatchee River basin assessment: Phase 1, QA/QC plan. Report to SFWMD, West Palm Beach, Florida.

Chamberlain, R.H. 1992. Freshwater discharges to the Caloosahatchee estuary. *In* Preliminary Report on Rainstorm June 23-30, 1992. Memorandum. SFWMD, West Palm Beach, Florida.

Clark, J.R. 1991. Mosquito control pesticides: adverse impacts to freshwater aquatic and marine organisms. Pages 33-39 *in* T.C. Emmel and J.C. Tucker, editors. Mosquito Control Pesticides: Ecological Impacts and Management Alternatives. Scientific Publishers, Gainesville, Florida.

Collier County, Pollution Control Department. 1993a. A preliminary assessment of estuarine water quality in Collier County: 1972-1990. Collier County Environmental Services Division Publication Series PC-AR-91-06.

Collier County, Pollution Control Department. 1993b. Strategic water quality monitoring plan, Collier County (Revision FY 92/93). Collier County Environmental Services Division Publication Series PC-SP-92-02.

CREW Trust. 1992. Conceptual management plan for Corkscrew Regional Ecosystem Watershed (CREW).

DeGrove, B., and F. Nearhoof. 1987. Water quality assessment for the Caloosahatchee River. Water Quality Technical Series Vol. 3, No. 19. FDER.

Drew, R.D., and N.S. Schomer. 1984. An ecological characterization of the Caloosahatchee River/Big Cypress watershed. FWS/OBS-82/58.2. FWS, Washington, D.C.

Duever, M.J., J.E. Carlson, and L.A. Riopelle. 1974. Water budgets and comparative study of virgin Corkscrew Swamp. Pages 595-634 *in* H.T. Odum et al., editors. Cypress Wetlands for Water Management, Recycling, and Conservation. First annual report to National Science Foundation and Rockefeller Foundation. Center for Wetlands, UF, Gainesville.

Facemire, C.F. 1993. Mercury concentrations in biota from J.N. "Ding" Darling National Wildlife Refuge; a baseline study. FWS, Vero Beach, Florida.

Florida Agricultural Statistics Service. 1994. 1994 Florida commercial citrus inventory. FASS, FDACS, Orlando, Florida.

Gee and Jenson. 1993. Corkscrew H & H study: executive summary. Job No. 91-293.01. Prepared for SFWMD, West Palm Beach, Florida.

Germain, G.J. 1994. Surface water quality monitoring network: South Florida Water Management District. Technical Memorandum. SFWMD, West Palm Beach, Florida.

Godschalk and Associates. 1988. Lee County Coastal Plan, Volumes I and II. Report to Lee County.

Hammett, K.M. 1990. Land use, water use, streamflow characteristics, and water quality characteristics of the Charlotte Harbor inflow area, Florida. Water Supply Paper 2359. USGS.

Harris, B.A., et al. 1983. Assessment of fisheries habitat: Charlotte Harbor and Lake Worth, Florida. Final Report. FDNR, Bureau of Marine Research.

Huegel, C.N. 1992. Bibliography. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Institute of Food and Agricultural Sciences. 1993. Citrus groves enhance wildlife. Newsline, September 1993. IFAS, UF, Gainesville, Florida.

Iverson, E.S., and A.W. Moffett. 1962. Estimation of abundance and mortality of a spotted seatrout population. Transactions of the American Fisheries Society 91:395-398.

Jodice, P.G.R., and S.R. Humphrey. 1992. Activity and diet of urban Big Cypress fox squirrels. Journal of Wildlife Management 56:685-692.

Jodice, P.G.R., and S.R. Humphrey. 1993. Activity and diet of urban Big Cypress fox squirrels: a reply. Journal of Wildlife Management 57:930-933.

Klein, H., M.C. Schroeder, and W.F. Lichtler. 1964. Geology and ground-water resources of Glades and Hendry counties, Florida. Florida Geological Survey, Tallahassee, Florida.

LaRose, H.R., and B.F. McPherson. 1983. Chemical and hydrologic assessment of the Caloosahatchee River basin, Lake Okeechobee to Franklin Lock, Florida. Water Resources Investigations Report 83-4126. USGS.

Lee County. 1994. Summary of the condition and quality of natural resources in Lee County. Lee County Planning Division.

Lee County and South Florida Water Management District. 1988. Six Mile Cypress Slough Preserve Land and Water Management Plan.

Mazzotti, F.J. 1992. Aquatic and terrestrial linkages: the importance of uplands for protecting wetland functions. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Mazzotti, F. J., and L.A. Brandt. 1992. Alternatives - a workbook for evaluating the effectiveness and feasibility of potential alternatives for integrating fish and wildlife resources with citrus development in southwest Florida. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Mazzotti, F.J., L.A. Brandt, L.G. Pearlstine, W.M. Kitchens, T.A. Obreza, F.C. Depkin, N.E. Morris, and C.E. Arnold. 1992 (released 1993). An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volumes I and II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

McNulty, J.K., W.N. Lindall Jr., and J.E. Sykes. 1972. Cooperative Gulf of Mexico estuarine inventory and study, Florida: Phase I, area description. NOAA Technical Report NMFS CIRC-368.

McPherson, B.F. 1994. National Water Quality Assessment Program -- southern Florida. Water Fact Sheet. Open-File Report 94-57. USGS.

McPherson, B.F., and R.L. Miller. 1987. The vertical attenuation of light in Charlotte Harbor, a shallow subtropical estuary, southwestern Florida. Estuarine, Coastal, and Shelf Science 25:721-737.

McPherson, B.F. and R.L. Miller. 1990. Nutrient distribution and variability in the Charlotte Harbor estuarine ecosystem, Florida. Water Resources Bulletin 26:67-80.

Montgomery, R.T., B.F. McPherson, and E.E. Emmons. 1991. Effects of nitrogen and phosphorus additions on phytoplankton productivity and chlorophyll *a* in a subtropical estuary, Charlotte Harbor, Florida. Water Resources Investigation Report 91-4077. USGS.

Morris, N.E. 1992. Design considerations for wetland protection in Southwest Florida citrus developments. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Morrison, D. 1989. Ecological assessment of the Cape Coral (Florida) residential waterway system. City of Cape Coral.

Morrison, D., J. Malsi, P. Renault, P. Light, and C. Marx. 1990. Effects of freshwater discharge from finger canals on estuarine seagrass and mangrove ecosystems in southwest Florida. Pages 115-126 *in* F.J. Webb, editor. Proceedings 17th Annual Conference on Wetlands Restoration and Creation. Hillsborough Community College, Tampa, Florida.

Noss, R.F., E.T. LaRoe III, and J.M. Scott. 1995. Endangered ecosystems of the United States: a preliminary assessment of loss and degradation. Biological Report 28. DOI, NBS, Washington, DC.

Obreza, T. 1992. Description and justification of citrus feasibility criteria. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Pearlstine, L.G., and W.M. Kitchens. 1992. Land cover and use. *In* An Evaluation of the Regional Effects of New Citrus Development on the Ecological Integrity of Wildlife Resources in Southwest Florida, Volume II. IFAS and Florida Cooperative Fish and Wildlife Unit, UF. Final Report, Contract #C89-0186, to SFWMD, West Palm Beach, Florida.

Pierce, R.H., R.C. Brown, K.R. Hardman, M.S. Henry, C.L. Palmer, T.W. Miller, and G. Wichterman. 1989. Fate and toxicity of temephos applied to an intertidal mangrove community. Journal American Mosquito Control Association 5:569-578.

Sawka, G.J., D.W. Black, and M.N. Allhands. 1994. Evaluation of wet detention for treatment of surface water runoff from a citrus grove in South Florida. SFWMD, West Palm Beach, Florida.

Science Sub-Group. 1993. Federal objectives for the South Florida Restoration. Report by the Science Sub-Group of the South Florida Management and Coordination Working Group.

South Florida Water Management District. 1992. Water supply needs and sources: 1990-2010. SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1993a. Save Our Rivers, Land for Waters' Sake: Five Year Plan. Department of Land Management, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1993b. Estuary Research Plan. Research Department, SFWMD, West Palm Beach, Florida.

South Florida Water Management District. 1994. Hydrologic restoration of southern Golden Gate Estates: quarterly subgrant performance report No. 1. SFWMD, Big Cypress Basin Office, Naples, Florida.

Southwest Florida Water Management District. 1993. Charlotte Harbor SWIM Plan. SWIM Department, SWFWMD, Tampa, Florida.

Wade, D., J. Ewel, and R. Hofstetter. 1980. Fire in South Florida ecosystems. USDA Forest Service General Technical Report SE-17.

Wiemeyer, S.N., C.M. Bunck, and C.J. Stafford. 1993. Environmental contaminants in bald eagle eggs--1980-84--and further interpretations of relationships of productivity and shell thickness. Archives of Environmental Contamination and Toxicology 24:213-227.